The evaluation of a novel haptic machining VR-based process planning system using an original process planning usability method.

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Abstract

This thesis provides an original piece of work and contribution to knowledge by creating a new process planning system; Haptic Aided Process Planning (HAPP). This system is based on the combination of haptics and virtual reality (VR). HAPP creates a simulative machining environment where Process plans are automatically generated from the real time logging of a user's interaction. Further, through the application of a novel usability test methodology, a deeper study of how this approach compares to conventional process planning was undertaken.

An abductive research approach was selected and an iterative and incremental development methodology chosen. Three development cycles were undertaken with evaluation studies carried out at the end of each. Each study, the pre-pilot, pilot and industrial, identified progressive refinements to both the usability of HAPP and the usability evaluation method itself.

HAPP provided process planners with an environment similar to which they are already familiar. Visual images were used to represent tools and material whilst a haptic interface enabled their movement and positioning by an operator in a manner comparable to their native setting. In this way an intuitive interface was developed that allowed users to plan the machining of parts consisting of features that can be machined on a pillar drill, $2^1/_2$D axis milling machine or centre lathe. The planning activities included single or multiple set ups, fixturing and sequencing of cutting operations. The logged information was parsed and output to a process plan including route sheets, operation sheets, tool lists and costing information, in a human readable format.

The system evaluation revealed that HAPP, from an expert planners perspective is perceived to be 70% more satisfying to use, 66% more efficient in completing process plans, primarily due to the reduced cognitive load, is more effective producing a higher quality output of information and is 20% more learnable than a traditional process planning approach.

Dedication

Many thanks to Professor Jim Ritchie and Dr Theo Lim for their support and guidance throughout this work. Also to my colleagues Ray, Zoe, Ying, Tom and Aparajithan for their help, support and company. I am particularly indebted to all the participants who generously gave their time and knowledge to help in the usability studies, without which much of this work would not have been possible.

Finally I would like to thank Heather my wife for her encouragement and patience.

Declaration

This is to declare that this thesis is an account of the author's work carried out at Heriot-Watt University, Edinburgh, except where acknowledgement is made, and has not been submitted for any other degree.

Craig Allen Fletcher (Candidate)

Professor James Ritchie (Supervisor)

Table of Contents

List of Tables

List of Figures

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Notation

HAPP	Haptic Aided Process Planning
VR	Virtual Reality
VE	Virtual Environment
CAPP	Computer Aided Process Planning
AI	Artificial Intelligence
NC	Numeric Control
CNC	Computer Numerical Control
DoF	Degrees of Freedom
OSG	Open Scene Graph
BSP	Binary Space Partition
CMM	Coordinate Measuring Machine
IQ	Information Quality
CC	Cognitive component
MC	Physical-motor component
TCT	Task Completion Time
HCI	Human Computer Interaction
SMEs	Small to Medium Sized Enterprises

VA	Virtual Assembly
GUI	Graphical User Interface
CAD	Computer Aided Design
SUS	System Usability Scale
TPMO	Time taken for Physical Motor Operations
TM	Time taken for Mental (cognitive) components
TR	Time taken for system to Respond

Chapter 1 Introduction

This chapter begins with the motivation for the work in this thesis followed by the statement of aims and objectives and concludes with a description of the thesis structure.

1.1 Motivation

Computer Aided Process Planning systems (CAPP) provide a necessary and important function in the preparation to manufacture products. These plans document clear and unambiguous data, providing justification for manufacturing decisions and recording specialist knowledge. This knowledge improves the speed and quality of manufacturing. In spite of the benefits and significant research effort, the uptake of CAPP systems by industry is slow [1] and virtually non-existent in small to medium sized enterprises (SMEs) [2]. This is one of the key motivations of this work: which aims to understand why and also to investigate the application of a new solution.

The majority of current CAPP research has and still focuses on the creation of automated systems based on Artificial Intelligence (AI), which extracts information from the upstream CAD generated file in order to apply a set of rules to calculate the downstream manufacturing instructions. The principal idea behind automated systems is to reduce the skill set required by a process planner and thus reduce labour costs; however, AI engines can only make decisions based on the information they have been given. This is a key issue with AI based systems as the transfer of this information is time consuming, labour intensive and requires specialist skills. For this reason many companies find it easier to rely on experts and their tacit knowledge of best practices to carry out process planning tasks; however the retention of that tacit knowledge can be problematic should the individual leave the company.

Alternatively, instead of attempting to replace the process planner with a fully automated system, an approach that enhances their skills and makes the planners more efficient and effective in their role could be developed. This type of system could take advantage of all their local expertise, whilst unobtrusively capturing and preserving that expert knowledge for later use.

Inspiration for this work was taken from the field of Virtual Assembly (VA) planning. By using VA techniques manufacturing engineers do not need to wait for physical prototypes to investigate the assembly sequences for parts. Engineers are free to experiment and investigate early on in the design process as soon as CAD models are created, without incurring cost or time delays. VA systems with the inclusion of haptic devices have demonstrated the ability of VR and haptics to not only promote understanding with reference to a specific problem but also capture that knowledge and formalize it into information rich instructions for downstream use.

This concept of applying VR to promote and document specialist knowledge is also applicable to process planning for machining, where billets are still mostly set up by hand before material removal takes place and cutting sequences or fixture plans can be investigated in a virtual environment.

The motivation for this work is to investigate a process planning system that, instead of attempting to replace the process planner and in the process losing local specialist knowledge, seeks to enhance and non-invasively capture the local planner's specialist knowledge in preparation for manufacture.

1.2 Research hypothesis, question and objectives

1.2.1 Research hypothesis

The hypothesis for this research was:
"A VR system with a haptic interface can provide a more usable process planning system than the most commonly used current approach."

1.2.2 Research aim

The aim of this research is to develop a 'proof of concept' haptic process planning system that can capture and formalize human expertise and to evaluate that system in order to gain an understanding of its performance.

1.2.3 Research questions

This aim framed the following research questions:

1. Can a haptic environment provide a process planning system that can automatically generate process plans by automatically logging and parsing the user's interactions?
2. Is this process planning system perceived to be satisfying, efficient and effective to use by process planners?

3. How does a haptic process planning environment compare to a commonly used process planning approach with regard to usability?

1.2.4 Research objectives

The following research objectives were defined:

1. The development of a haptic aided process planning system research platform embedding desired process planning operational features such as: job set-up, machining, job tear down, time and cost estimation and automatic plan generation.
2. To define, develop and implement an experimental methodology, including usability measures, which independent of the system platform allow process planning system usability evaluation with regard to satisfaction of use, efficiency and effectiveness.
3. The cross comparison of the two systems and the statistical analysis of any output ensuring robust comparative results.

1.3 Thesis structure

CHAPTER 2 defines the functionality and reviews the state of the art of CAPP systems. Current issues and research areas are discussed.

CHAPTER 3 provides an initial overview of Virtual Reality (VR) and haptic technologies. This is followed by an investigation into the state of the art of haptic VR systems applicable to process planning in a machining environment.

CHAPTER 4 undertakes a description and justification of the research approach and methodology. Tools for the incremental development of exploratory software are discussed along with system evaluation. The requirement for a systematic approach for cross platform comparison is highlighted and why comparison against a traditional process planning system is necessary.

CHAPTER 5 sets out a brief description of the requirements for a haptic VR system suitable for process planning followed by a description of the initial system design and the results of a pre-pilot study.

CHAPTER 6 documents the changes made to the evaluation method and the application based on findings in the pre-pilot study and outlines a more in depth pilot study. The pilot study includes a larger number of participants to test the system and outlines a comparative assessment against a traditional process planning system.

CHAPTER 7 documents and implements changes made to the evaluation method and application based on changes identified in the pilot study then describes the results of an industrial trial with professional machinists and more complicated machining sequences.

CHAPTER 8 discusses the results with regard to the research hypothesis, questions and objectives.

CHAPTER 9 draws together the conclusions, highlights the contribution of the thesis and identifies important future work.

Chapter 2 A review of process planning

2.1 Introduction

Process planning is critical in modern manufacturing environments, bringing improvements in cost, quality and time to market. Process planning is the interface between design and manufacturing, especially for machined parts. This is the phase in a product's development where the selection and sequencing of operations and associated processes transform a material into a finished product [3]. A further development to process planning systems was CAPP. These were proposed by Niebel [4] almost fifty years ago to address some of the short comings of process planning systems; however, the commercial uptake of CAPP does not reflect the research effort that has since been expended. The question addressed in this chapter is why?

2.2 Process planning system - essential requirements

The process to create a plan can be broken down into several sub-phases as defined by Scallan [3] and Ritchie [5] and as outlined through discussions with expert process planners as part of this research, it is these sub-phases that make up the essential requirements of a process planning system:

1. **Drawing Interpretation and material evaluation**: This is where the drawing is analysed and the best material for the job selected. Factors affecting the material choice could include weight, durability or cost.
2. **Process selection and sequencing**: There may be many processes involved in manufacturing a product; these could include forging, welding, casting, painting/treating, turning, drilling or milling. Each of these processes can impact the other so the sequence of operations is important. An example of this based on anecdotal evidence from discussions with machinists where a job has been turned before being drilled resulting in a slightly more complicated clamping strategy for the drilling sequence. This may have been simplified with better process sequencing.
3. **Machine and operations sequencing**: This includes machine selection and the definition of the sequence of operations to be carried out on the machine. Operations may include milling, drilling or turning. The sequence of these operations is important, as again the clamping strategy could be affected.
4. **Tooling selection**: Selecting the correct tool is important: factors that affect tooling selection include surface finish, machining speed and tool access.

5. **Setting of process parameters**: Once the tool has been selected the feeds and speeds are selected to achieve the correct surface finish and tolerance. Once selected an accurate calculation of machining time can be made which enables job costing and the measurement of tool wear.
6. **Determination of work holding requirements and set up time calculation**: The determination of work holding requirements and set up time calculation is critical to job cost and quality. This area, which includes the set-up, fixturing and teardown of the work piece between machining operations, is time consuming; often taking several days to finalise the design of a fixture, inherently reliant on experience, requiring a planner with at least ten years manufacturing knowledge [6], and can account for 10-20% of the total cost of a manufacturing process [7].
7. **Selection of quality assurance methods**: This involves the selection of inspection type, methods, location and tools required. Inspection methods could include the use of go/no go gauges at specific points during manufacture or the use of variable gauges to measure dimensions.
8. **Plan documentation**: Correctly documenting the plan is critical, this is how engineering knowledge is captured and best practice evolves. The documentation provides an interface to the next stage of manufacture, so it should be of high quality in a format that can easily be processed. This can be in the form of a process plan which may include numeric control (NC) code for computer numerical control (CNC) machining.
9. **Costing the plan**: Effective job costing enables a company to select the most appropriate process plan, track costs more effectively, prioritise jobs and also quote more accurately. Costing should include the entire job from set up to tear down.

These sub-phases are not necessarily sequential, they can be iterated through in various stages depending on the quantity and complexity of the product, and its associated data before finalization.

2.3 Approaches to process planning

Combining their knowledge of manufacturing processes and their understanding of the job requirements, process plans are traditionally created by experienced process planners and then sent to the shop floor for actual product manufacturing. However, this type of planning can be inconsistent, suffering from excessive clerical content and is dependent on the knowledge of the planner.

With the introduction of affordable PC systems, CAPP software was developed to try and remove these problems. Variant CAPP systems formed a part of this early software development. These systems are knowledge based, copying and amending plans from previous designs to generate new versions visually via the use of a classification code [8]. This type of system enabled proven prior knowledge to be drawn into the new design; however, it is still time consuming to acquire the manufacturing database on which they depend in the first place.

A parallel development for process planning software was generative CAPP [8] where, prior captured knowledge is embedded in the generative system and a new plan for each job created. These systems rely on some form of AI aim to remove human intervention and develop unique plans directly from the design model files or product data each time they are created or generated. This reduces the time taken to acquire the manufacturing information as the associated knowledge is already embedded into the system in advance. However this technology still faces major challenges in feature extraction and knowledge maintenance and application [9] and the plans are generally tied to a very specific set of processes or product family needing some form of manual input for completion.

2.3.1 A CAPP system description

The input to and output from a CAPP system [10] is illustrated in Figure 1. However, this can be further refined for more generic CAPP systems by removing shop floor status as an input to process planning and moving it to an input of manufacture scheduling; this is also supported by the previous literature documenting the requirements of a process planning system (see 2.2), where no mention of shop floor status is made. A further key input added to the definition of any CAPP system should be specialist knowledge which would allow systems to incorporate company specific strategies with the process plans output reflecting this. With regard to the system outputs; costing should also be included as an output because in a competitive environment this is one of the most important factors that may seriously impact the process plan selected and the documentation should be extended to include that necessary for non-numerically controlled machine based processes as well.

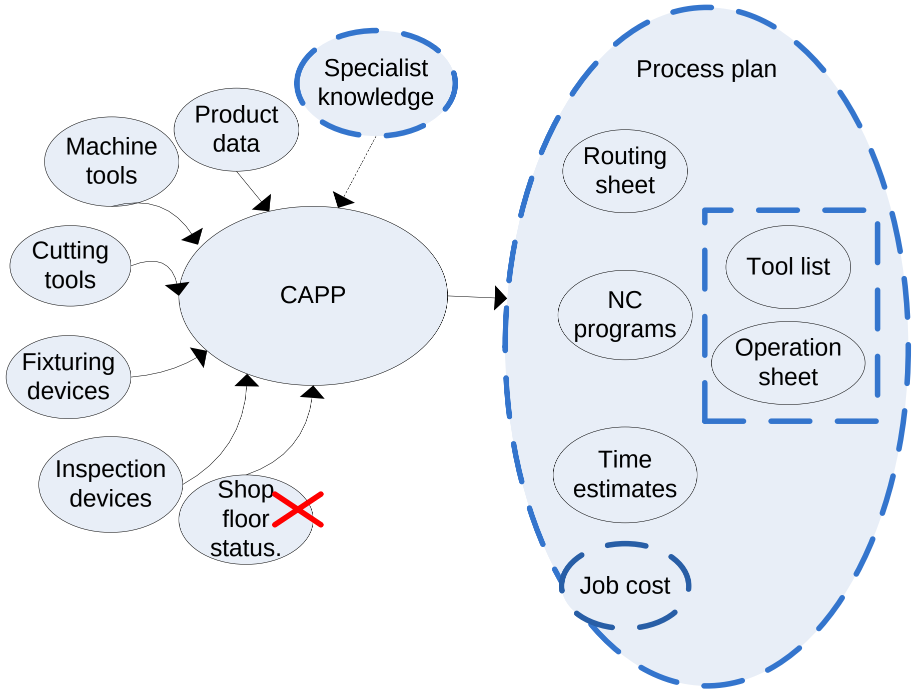


Figure 1 CAPP system derived from [10]

2.3.2 A CAPP system - desirable characteristics

In addition to the essential requirements described in 2.2 some of the desirable characteristics of CAPP systems have been highlighted in [9] which is illustrated and reproduced in Figure 2. These characteristics are not considered essential as a CAPP system can function without them however the system may not be easily implementable or usable by operators.

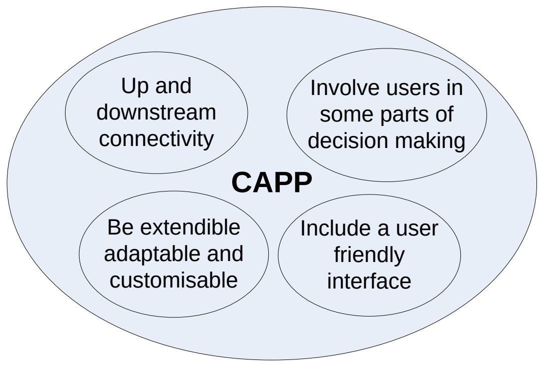


Figure 2 Desirable characteristics of a CAPP system derived from [9]

These are further supported by previous CAPP literature reviews with Cay [10] stating "The users must be allowed to select the subsystems and manufacturing domains they need, and must be given the capability to tailor system environment and operation considering their own design and manufacturing practices" and Kamrani [11] who points out that CAPP systems should be "Commercially available and user friendly".

2.4 Commercial application of process planning

Commercial approaches to process planning consist of both traditional methods and CAPP. CAPP systems are often embedded into tools such as CATIA, Creo or EdgeCAM; however this tends to focus on the generation of machining instructions for specific CNC processes not including all the functionality for the essential requirements for a true process planning system as derived previously and relies on windows style interfaces to meet the desirable characteristics of a CAPP system (2.3.2). Xu et al [9] go further stating that these systems are not true systems since their unstructured and unsystematic approach has hindered the growth of CAPP as a whole. A summary of commercial tools and their embedded functionality is illustrated in Table 1.

Table 1 Summary of process planning approaches and essential requirements

	Commercial process planning approaches			
	Traditional	CATIA	Creo	EdgeCAM
Process planning essential requirements				
Drawing interpretation and material evaluation.	x	x	x	x
Process selection and sequencing.	x			
Machine selection and operations sequencing.	x	x	x	x
Tooling selection.	x	x	x	x
Setting the process parameters.	x	x	x	x
Calculate machining times	x	x	x	x
Determining the work holding requirements.	x	x	x	x
Calculate set up time	x			
Selecting quality assurance methods.	x			
Documenting the process plan.	x	x[1]	x[1]	x[1]
Costing the plan.	x			
Process planning desirable characteristics specific to user				
Involve user in some part of the decision making process	x	x	x	x
Include a user friendly interface				
Strength with which requirement/characteristic is met	Weak		Strong	

In practice it appears that large manufacturers implement a mix of CAPP systems with expert engineer intervention where necessary [12] in contrast, small to medium size enterprises (SMEs) do not use CAPP systems at all but tend to rely on traditional process planning methods [2]. Further evidence for the low commercial uptake of CAPP systems was gathered via telephone interviews carried as part of this research. Of the seventeen companies surveyed fourteen indicated they did not use CAPP software whilst three indicated they did, non-CAM integrated CAPP systems used by participants interviewed include e-max [13] and e2i [14]. The survey found 5 main reasons for this low uptake of CAPP were: (i) no expected time saving; (ii) they require considerable training; (iii) systems are too inflexible (unable to quote

[1] NC code primarily

was one example of inflexibility), (iv) systems are difficult to implement; and (v) the final results are not always optimal. In two cases cost was also mentioned but has not been included as this is a financial aspect that cannot be addressed by research. This survey, Table 2 supports the low commercial uptake of CAPP systems as reported in [2].

Table 2 Surveyed process planning approaches

Process planning approach	Number of companies (Total 17)
Traditional approaches	14
CAPP approaches	3

All of the reasons given in the survey shown in Figure 3 can be traced back to the desirable characteristics of a CAPP system (Figure 2).

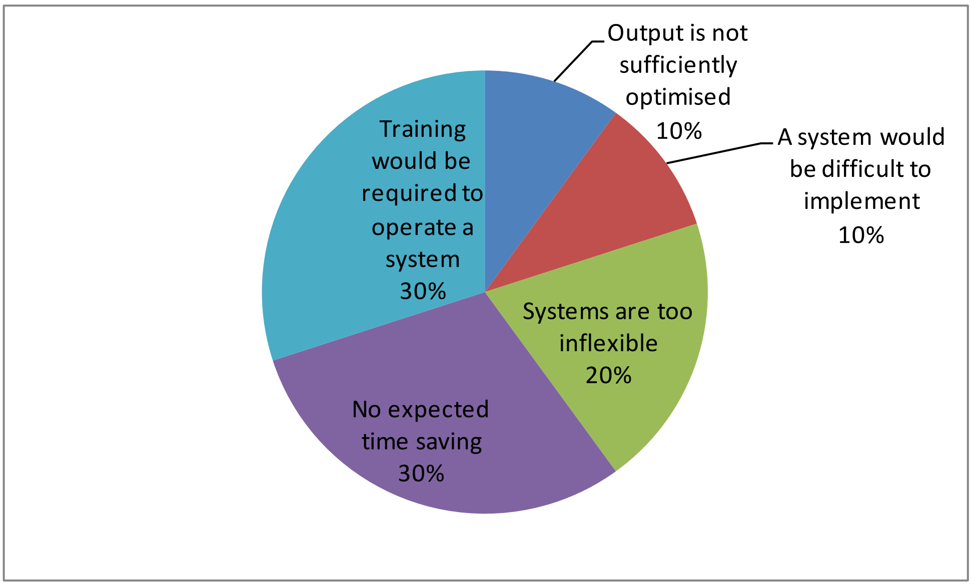


Figure 3 Survey of reasons for non-implementation of CAPP systems

The survey not only supports the failure of CAPP systems to address the desirable characteristics of a CAPP system as defined in Figure 2 but also reveals more detailed information with regard to those characteristics and further extends the definition of two of them. Where 'difficult to implement' and 'too inflexible' were cited, these issues can be categorized as a failure to meet the desirable characteristic of 'extendibility, adaptable and customizable'. Those reasons citing 'training effort would be required' and 'no time saving expected' can be categorized as a failure to meet the desirable characteristic of a user friendly interface; if the user interface was easy to use it would be quick and intuitive with no training required; however a user friendly interface is probably not a sufficiently strong description of the type of interface that is really required, after all a fully automated system with one button would be very user friendly. What participants indicated, was the need for an interface that allows the operator not only to be able to become accustomed to it quickly and without training but that it is also highly immersive allowing the operator a thorough understanding of the machining processes and the ability to maintain their intimate machining skill base. Perhaps a user friendly interface that is immersive and knowledge enhancing would be a better description. Finally those citing 'insufficiently optimized output' is likely due to a failure to include local specialist knowledge; it is probable the operator felt they could generate a more optimal plan than that operated by the CAPP system. This again builds on and adds more detail to the desirable characteristic of including the operator in the decision making process. However, it is insufficient to only state that a desirable characteristic is to include the planner in the decision making process, a stronger definition is required further clarifying that not only should the operator be included in the decision making process but that decision making process should aim to draw in and maintain the local specialist knowledge and company practises known by the operator.

2.5 Current trends in CAPP research

The previous sections in this chapter have reviewed the fundamental approaches to CAPP showing that commercial uptake is low and also some of the reasons why. The following section discusses the current CAPP research to ascertain how and if the previously highlighted issues are being addressed.

Recent surveys by Xu et al [9] and Yusof et al [15] have classified current trends over the last 5 years in CAPP research with regard to technology and systems. An overview of the technologies and an indication of their main focus are given in Table 3.

Table 3 CAPP research trends over last 5 years

CAPP technology	**Description**	**Research focus**	
		Essential CAPP requirements	**Desirable CAPP characteristics**
Feature based technologies	Feature based technologies involve the identification of features to be machined on the part. Feature recognition is used in generative and variant systems for both the identification and classification of machinable features, and pattern matching (finding parts with similar geometry). This allows the CAPP system to associate known machining methods with specific part geometry: however feature recognition is not trivial and still pose a significant research challenge [16].	Tool selection, operation sequencing [17], process parameters and work holding [18].	No
Knowledge	Knowledge based systems include a large	Tool	No

based systems (or expert systems):	knowledge base of solutions from within the manufacturing domain, an inference engine and a user interface. The inference engine is used to perform a task in the same way a human would. These systems allow the inclusion of experience and knowledge, which can be added to over time.	selection, operation sequencing [19], work holding and process parameters [20].	
Neural networks	Neural networks attempt to imitate the way the human brain works. Processing elements are connected and the organization and weight of the connections determine the output. They are effective at predicting events from a large database of prior examples and well suited to the dynamic and changing environment of manufacturing. It should be noted that these systems require training.	Tool selection, operation sequencing [21], work holding [22] and process parameters [23].	No
Genetic algorithms	Genetic algorithms are based on evolutionary selection. A set of ideal manufacturing criteria is defined; each process then contains information that defines how well it can meet the defined criteria. The processes are then ranked by fitness with regard to the selected task, the most suitable processes are selected and a new solution evolved, possibly with some degree of mutation included. Genetic algorithms are more efficient as they do not apply an exhaustive search of all possible solutions but try to intelligently find the best solution and can evaluate potential solution simultaneously; the predicate of evolution is to try all options simultaneously and the first to reach a solution wins.	Process route[24], tool selection, operation sequencing, machine selection, work holding, process parameters [25].	No
Fuzzy set theory/logic	Fuzzy set theory/logic attempts to present problems to a computer to allow them to be solved in a manner similar to humans. Data is not defined as true or false but as degrees of truth. Many partial truths are accumulated which when a certain threshold is reached result in a higher level of truth or an action. Fuzzy logic like neural networks is suitable for adaptive and learning environments being particularly good for solving unclear or ambiguous problems.	Operation selection, costing [26], machine selection and process parameters [27]	No
A petri net	A petri net is a mathematical modelling language for modelling distributed systems; it is very similar to a state transition diagram and is effective at modelling systems with concurrent states that require synchronization. Petri nets enable the modelling of dynamic manufacturing environments.	Costing, operation sequencing [28] and process parameters [29].	No

Agent based technology	Agent based technology implement agents which are a form of software abstraction and have a defined behaviour. Agents are autonomous and will act based on information received and their own self-interest. These systems can provide robust solutions for open and dynamic environments where adaption is required.	Machine selection, Operation sequencing [30] process parameters and costing [31].	No
Internet based technologies	Internet based technologies have been developed to support process planning, these improve communication and cooperation.	Set up planning [32], machine selection and operation sequencing [33].	Involve users in some part of the decision making process
Standard for Exchange of Product Model Data (STEP) compliant CAPP	STEP is an International Standard Organisation (ISO) defined standard for the exchange of model data aiming to overcome incompatibilities in model representation which have reduced the effectiveness of information exchange between manufacturing applications. STEP defines an information format that captures all the information necessary to manufacture a product in a platform independent format. STEP consists of many differing Application Protocols (AP) applicable to different areas of manufacture; AP240 is relevant to process planning [34]. Many of the process planning environments developed around STEP use feature based methodologies.	Set up [35], operation sequencing, process selection , tool selection and process parameters [32].	Upstream and downstream connectivity.
Functional blocks	Functional blocks describe the function between input and output data for a specific functional part of a system; these are used to create a multi-tier approach to process planning, for example a system may have a higher level tier for shop floor planning and a lower level at the machine level. Functional blocks allow modular systems to be created.	Process sequencing, operation sequencing [38].	Extendible, customizable and adaptable.

It can be seen from Table 3 that the primary focus for CAPP systems research by technology type is focused on meeting the essential requirements of a process planning system, with the majority of current research not addressing the reasons identified for low uptake of CAPP systems shown in Figure 3. Two key failings are the inclusion of the process planner in the decision making process and the investigation of user friendly interfaces.

A technology that is not mentioned by either Xu or Yusof is the application of VR to CAPP. An early attempt of a VR style CAPP interface was created by Peng et al [39] who saw VR as a tool which could provide flexible visualisation and simulation to improve process planning and also training of engineers and the workforce. They found that VR provided immediate feedback of manufacturing know how in early stages which enhanced quick decision making and that VR also facilitated information sharing through an Intranet. They concluded that the development and application of VR technology enhances the capability of the engineering simulation process. Although this research is a step in the right direction it is difficult to see true levels of sophistication since the interaction remained limited to machining processes defined by an AI engine with the operator constrained to input through the mouse and keyboard. Since Peng, new approaches for the input of VR systems have been developed offering more interactive, immersive interfaces to VR systems in the form of haptic devices [40]. These types of devices integrate the sense of touch into a VR system allowing the operator to interact with objects in the VE in a more natural way potentially providing a user friendly way to integrate the planner into the decision making process.

2.6 Summary

Although an investigation into some commercial CAPP systems indicates a lack of process planning essential requirements, this does not seem to be the reasons highlighted by users surveyed for their low uptake. Indeed, the interviewees cited a lack of the desirable characteristics as more significant. Not only did the survey reveal that a system that is more user-friendly, requiring less training and is more efficient to use, easy to implement, flexible and able to include better specialist knowledge for producing a more optimised output is of higher priority than a full suite meeting all of the CAPP essential requirements; but it further redefined some of the CAPP desirable characteristics as stated in the literature review. The survey found that not only should the interface be user friendly but also highly immersive with the ability to enable the operator to maintain a close link with the low level machining processes and maintain their skill base. The survey also redefines the CAPP desirable characteristic that states 'the operator should be included in the decision making process' to 'the operators local and specialist knowledge should be drawn into and maintained in the decision making process'. It can be seen from the literature review that CAPP research is still primarily focused on automating the essential requirements of CAPP systems and is not investigating the desirable characteristics. Therefore this research addresses a gap in current CAPP research by developing and evaluating a haptic VR system, Haptic Aided Process Planning (HAPP) that explores factors relevant to the desirable characteristics of a CAPP system.

Chapter 3 A review and critique of haptic VR literature relevant to process planning

3.1 Introduction

As highlighted in the previous chapter current CAPP research does not focus on the desirable characteristics of CAPP systems but on its essential requirements. It was suggested that haptic VR might address some of these desirable characteristics by offering a user friendly interface and involving the operator in the decision making process. This chapter starts with an overview of Virtual Environments (VE), haptics and the benefits realised by a haptic VR system. This is followed by a review of haptic VR literature relevant to process planning, identifying how researchers have applied haptic VR to planning and related areas that potentially meet the functionality of the essential requirements of a process planning system. Finally the chapter closes with a review of approaches used by researchers to capture the usability of haptic systems.

3.2 Virtual Reality (VR)

Virtual Reality (VR) can be loosely defined as the creation in software of a real world situation [41]. One of the key attributes in the requirements of any VR environment is that the experience needs to be convincing, which should not to be confused with realistic. According to Sherman et al [41] there are four elements required to create a convincing virtual reality experience: a virtual world, immersion, sensory feedback and interactivity.

- The virtual world is the setting for the virtual environment, where the events take place.
- Immersion is the sensation the user must have of being in the environment (the word sensation is key not to be confused with belief).
- Sensory feedback is where the virtual environment provides feedback to one or more of the operator’s primary senses (these include sight, sound, touch, taste and smell).
- Interactivity is where the system must provide a response to the user's actions.

Figure 4 Virtual Reality Environments

An illustration of a typical VR system and the potential means of input and feedback are illustrated in Figure 4. The virtual world is created inside the computer. The feedback is through: head mounted displays, monitors or CAVE environments, speakers and, less commonly, haptic devices. Input is achieved by voice, physical controllers and/or tracking sensors. The interactivity is derived from the mixture of input and feedback with an operator carrying out an action in the virtual world and then receiving feedback as to its effect. The sense of immersion comes from the interactivity with the virtual world. VR systems are classified into two types; immersive, where the user has no visual contact with the physical world and a CAVE or head mounted display is used for visual stimulus, or desktop where a monitor is used [42].

A haptic interface allows interaction with the system through the sense of touch. A German philosopher, Max Dessoir, first proposed the term haptic with regard to this particular sense. Although haptic is a Greek word, relating to physical contact or touch, in this context the term haptic includes not only contact and pressure stimuli but also the user [43].

Humans use their sense of touch, along with the other senses, to improve their perception of the world around them. Although vision provides very rich and contextual information its ability to provide this with regard to material qualities is limited. By actively exploring objects by hand, information regarding qualities such as texture, hardness, temperature, weight, volume, global shape and exact shape can be obtained [44]. It is the human haptic system that allows a person to grasp and engage with objects [45] and move and rearrange them within a physical world, removing any visual ambiguities that might occur [46]. The haptic sense builds on numerous tactile and kinaesthetic signals; the brain picks up these clues and ignores those that are not consistent with what the perceptual system expects [47].

It has been found that by incorporating haptic interfaces into VR that:

- task performance has been enhanced in 3D environments where quick and accurate movement is required [48];
- visual load has been alleviated, by allowing the passing of an extra channel of information [49] which results in the perception of a reduced workload [50].
- objects can be manipulated in a more intuitive manner when compared with a mouse and keyboard [51].

Haptic devices are mechanical pieces of equipment that provide interactive feedback to the operator when connected to a virtual environment. As described by Srinivasan [52], haptic interfaces have two basic functions: " ...(1) to measure the positions and contact forces (and time derivatives) of the user's hand (and/or other body parts) and (2) to display contact forces and positions (and/or their spatial and temporal distributions) to the user."

Haptic interfaces come in many different forms and are capable of providing differing combinations of tactile and/or kinematic feedback; a review of these is given in [40]. The specific nature of the device depends on the user's requirements. There are several commercial haptic devices manufacturers: Haption [53], Sensable [54], Novint [55] and Immersion [56]; however these are not always suitable for specific needs and many researchers have developed their own. A combination of the various categories of haptic device derived from [57] [58] is given in the overview of devices available as shown in Figure 5. Grounded devices are considered to be devices set onto a fixed surface, mobile devices are devices carried by the user and non-mobile devices, larger scale devices that are typically fixed in a location. Grounded devices allow internally unbalanced forces to be modelled, such as pressing a button with a single finger whereas mobile devices require internally balanced forces such as the picking up or grasping an object. The main advantage for mobile devices is their larger workspace [57].

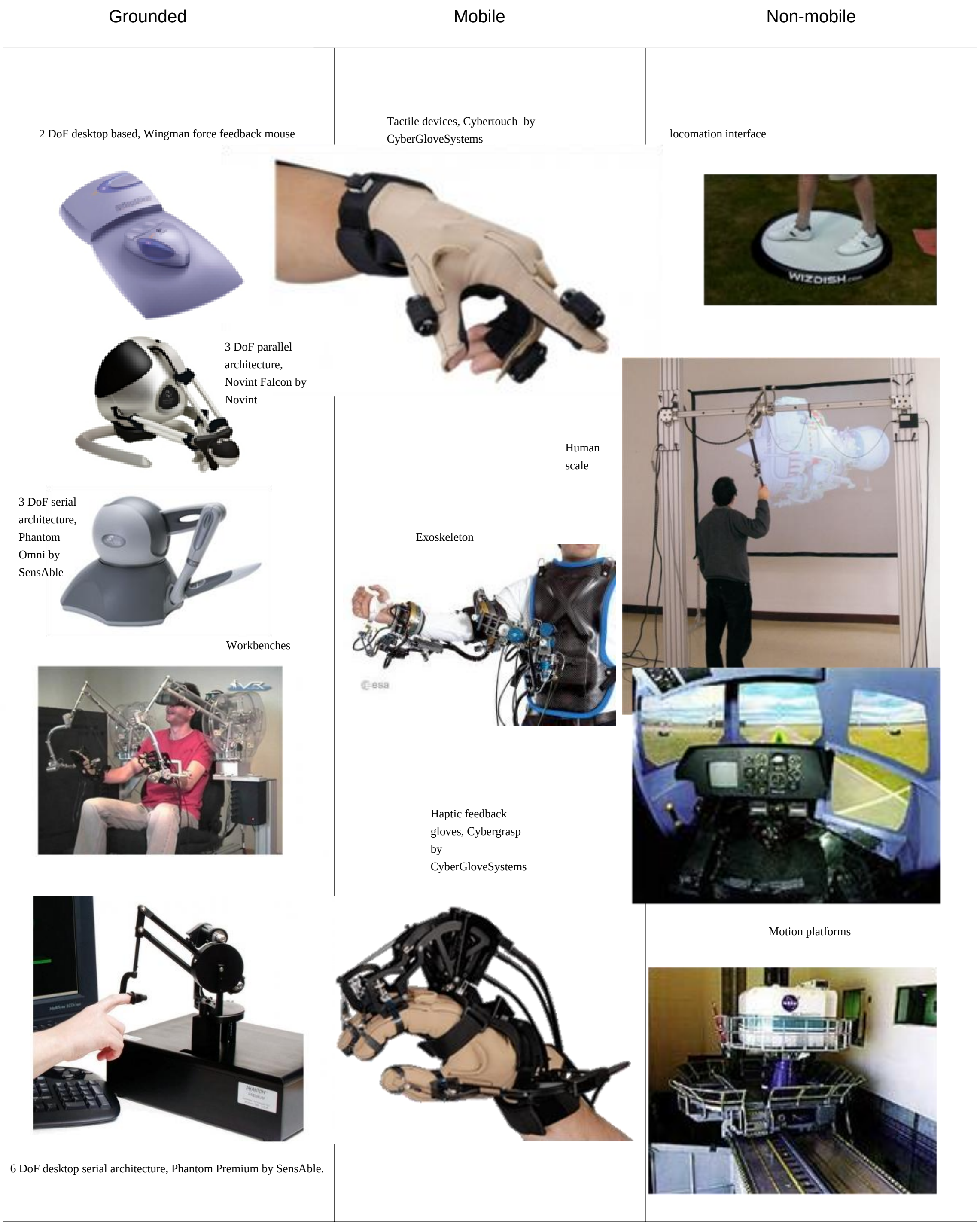


Figure 5 Illustration of haptic devices [54],[58-62]

Grounded devices, specifically desktop grounded devices, have varying degrees of freedom (DoF) depending on the task requirement. It should be noted that although some devices are marketed as 6 DoF this may only refer to the input whereas the feedback remains 3 DoF. Devices with 3 DoF are able to model linear forces whereas 6 DoF devices are also able to model torque. Grounded haptic devices have either a serial or parallel mechanism. Serial mechanisms are more compact and can be fast; however as each section is added to the chain the total inertia of the system increases and the total stiffness that can be modelled decreases. Parallel mechanisms do not exhibit the above problem and have a much higher capability to model stiffness due to a stronger and more compact architecture. The disadvantage over serial mechanisms is that the mechanism's elements can physically interfere with each other [58].

In general haptic devices should have low inertia and friction, i.e. free movement should feel free. The systems should be capable of a high degree of stiffness allowing a hard surface to feel firm with no unintended vibrations rendered. The systems should be safe to use with low backlash and only operating within force ranges that are safe for the operator. The device should provide a good match, rendering forces with the correct magnitude and resolution for the human haptic system sensors they are intended to simulate [58][64][52].

3.3 Haptic virtual reality and planning

Two areas that have seen significant research through the application of haptic devices and VR are surgical planning and assembly planning.

3.3.1 Haptic virtual reality and surgical planning

Haptics have a history of development within surgical planning and training. Fundamentally surgery and machining products are quite similar since both require drawing/x-ray interpretation, process selection and sequencing, tooling selection, the setting of process parameters and the specification of work holding requirements. In general haptic VR surgical planning systems are not used to generate instructions but to aid surgeons visualising and preparing for complicated surgery. An illustration of some surgical applications and the benefits realised follows:

A haptic assisted surgical planning system was developed by Olsson et al [65] to aid surgeons with patient specific, pre-operative planning for cranio-maxillofacial (CMF) surgery. This type of surgery aims to restore the normal skeletal anatomy in patients with serious facial trauma. The surgeon found the system aided the understanding of the complexity of the case and provided an insight into the preferred sequence of reconstruction. The haptic device specifically aided fragment placement; a snap to fit approach was investigated but was found not to give robust results for small fragments. Another example of haptics and VR for surgical planning is outlined by Fornaro et al [66]. This system was developed to plan the reduction of acetabular fractures and demonstrated that a haptic VR environment could become a useful step in a surgical planning work flow. The haptic device allowed surgeons to manipulate images of bone fragments and collect information to create osteosynthesis implants, which work as a fixture to attach bone fragments, in advance of the surgery. It was highlighted that virtual planning in surgery leads to a better understanding of the fracture and leads to more accurate and efficient reductions, the haptic device gave the surgeon an insight into the spatial relation of fracture fragments and helped in selecting the operative approach.

The ability for dental surgeons to practise and plan was demonstrated in an initial study by Xiaojun et al [67] who developed a modular piece of software named CAPPOIS (Computer Assisted Preoperative Planning for Oral Implant Surgery). The potential for haptic devices to enable surgeons to differentiate between tissue types is discussed and how this will aid in the calculation of force in cutting, clamping or suturing. Although a limited study, CAPPOIS was found particularly useful by inexperienced surgeons in enabling them to improve their skills before the dental implant surgery.

A decade of researching surgical planning is reported by Montgomery et al [68]. In this paper it is concluded that interaction is key in surgical planning, interaction is also a major aspect in convincing virtual environments (3.2): so it can be seen both tasks share key functionality. Montgomery also indicated that the planning environment can be an abstract process and that actual simulation of reality is not required: a factor also supported in the requirements to create a convincing virtual environment (3.2). Haptic devices are used in their planning system and it was found effective for rotating and translating models for better visualization. It also enabled operators to push, pull, manipulate and segment data efficiently. After nearly 40 cases of virtual environment surgical planning Montgomery et al are convinced that computer-based visualization and interaction for surgical planning will provide a better outcome for the patient, with less time in the operating theatre, reducing cost and decreasing the risk to the patient.

The benefits realised by haptic VR in surgical planning such as: improved problem visualization, better understanding of problem and associated complexity, training and planning in advance are also applicable in CAPP. The fact that these benefits have been seen to result in more accurate and efficient solutions may address one of the unmet desirable CAPP requirements that was highlighted in Chapter 2 (Figure 3), where poorly optimised results was highlighted as one of the reasons for low uptake and this may be achieved by including the planner in the decision making process through haptic VR.

3.3.2 Haptic virtual reality and virtual assembly

Virtual assembly planning is defined by Seth et al [69] as "...the capability to assemble virtual representations of physical models through simulating realistic environment behaviour and part interaction to reduce the need for physical assembly prototyping resulting in the ability to make more encompassing design/assembly decisions in an immersive computer-generated environment." The benefits highlighted in the definition are equally applicable to process planning for machining, particularly set up and teardown, as it is similar to assembly planning; billets and fixtures need to be assembled before material removal is carried out and the plans to manufacture the part need to be documented [3][5]. A justification for virtual assembly is given by Seth since (i) VA addresses the issue of including local expert knowledge which automated Computer Aided Assembly Planning systems (CAAP) do not take into account; (ii) human input is critical in reaching effective and efficient solutions particularly as solutions become more complex; (iii) CAD systems fail to provide sufficient spatial awareness reducing the planner's ability to understand issues such as access; (iv) virtual systems allow early prototyping through the use of CAD models instead of having to wait for physical mock ups; (v) expert knowledge, that is typically difficult to document can be captured by an expert simulating an assembly sequence. Constraint and physical-based modelling is also highlighted and it is concluded that although constraint based applications enable quick and accurate part positioning, physical based models allow for more realistic modelling. However, physical based modelling is highly intensive and a good future direction would be a mix of constraint and physics-based modelling.

In a dual haptic VA planning and prototyping environment called SHARP [70], several assembly scenarios of complex CAD models were carried out. The lack of 6 DoF is found to be important, with 3DoF no torque can be felt during collisions and this limitation was found to feel restrictive. The haptic models are generated from the CAD files as a voxel-based image. These are only approximations and the inaccuracy of these models caused dimensional errors during close fitting assembly operations. Howard and Vance [71] developed a desktop virtual assembly system with physical-based modelling. The benefit of haptic force feedback was tested by placing a bolt in a hole. It was found the force feedback provided more natural interaction by feeding back instantaneous collision cues, helped guide the user's motion that would otherwise rely on delayed visual clues and helped guide the user's motion once a bolt had been partially inserted. The environment was also stress tested to identify limiting factors. During model load testing for large models, i.e. a polygon count > 60,000, either the graphics or physics threads were found to be the limiting factor but never the haptic rendering thread. One solution to reduce the loading on the physics thread was to use a mixture of primitive shapes and polygon meshes and to use only dynamic models where collision response is necessary.

An investigation by Lim et al [72] demonstrated that by logging the virtual interactions of an operator assembling a peg into a hole with their Haptic Assembly Test bed (HAT) and comparing this to a real life activity, training carried out in the VE enhanced real life task performance. Further, in a usability study carried out by users in the experiment it was indicated that HAT was found to be an intuitive system to use. This was later extended to incorporate therbligs and chronocycles to aid the capture of the type of movement logged in the virtual world [73] and to automatically codify this information into a written description or plan. A further piece of work by the same authors, develop a virtual assembly system for the generation of assembly plans [74]. In this application a gear pump was assembled and assembly instructions automatically derived, including information such as: operation number, work centre, assembly instruction, tooling, virtual and actual assembly time. Assembly knowledge was stored as a sequence of written instructions and pictures.

Although non-haptic a few other pieces of research are worthy of mention. In the non-haptic system developed by Long et al [75] a human operator assembles a nuclear machine and it is demonstrated how video clips can be used to record knowledge generated during the planning and allow easy reuse for later planning, training and evaluation. A further non-haptic immersive VR system developed and investigated by Ritchie et al [76] demonstrates how human expertise was captured in the assembly of small mass producible parts and formalized into a series of assembly sequences including actions, times and connections plus a bill of materials in an html format; this research aimed to capitalize on VR to gain assembly knowledge early on in the design process. These applications allow the capture and formalisation of human expertise but Sung et al [77] takes this one step further, by applying a time and motion study to analyse captured expertise in order to improve the captured information for product assembly and the generation of assembly instructions.

Haptic VA applications provide further validation of the benefits that haptics and VR can bring to the planning process. The VA literature adds to that of surgical planning indicating that haptic VR provides an intuitive user interface that can improve real life task performance. Further work has been carried out within the VA literature regarding physical modelling as this is considered to provide a more natural form of human/system interaction: However, one of the key advantages to be drawn from the haptic VA literature is how these applications have been used to capture and document local expert knowledge into a set of instructions or assembly plans and times.

3.4 Haptic virtual reality applications relevant to the essential requirements of a process planning system

As was highlighted previously an initial attempt to integrate CAPP and VR was undertaken by Peng et al [39]; however, this paper primarily discusses the advantages of CAPP and VR and proposes an architecture and functionality. The actual application is limited to the simulation and validation of an NC machining task with no output and a mouse and keyboard as an input device. A wider search of relevant literature reveals no specific work on CAPP and VR: however, research has been carried out in individual areas that can be related to areas that make up the functionality to meet the essential requirements of a CAPP system.

3.4.1 Haptic virtual reality and machining

Within virtual machining, there are several applications of interest. Haptics were demonstrated to provide a more user friendly interface to interact with 3D graphics whilst capturing human expertise relevant to a 5 axis milling machine tool path by Chen et al [78]. Chen demonstrates that by the use of haptic guiding forces, the operator's work load was reduced and that novice and expert alike were able to easily generate and plan collision free 5-axis tool paths with the user's interaction accurately captured. However, this work primarily concentrates on optimising collision detection by mesh re-sampling of the billet model, an implicit model representation of the tool geometry and the creation of haptic constraints/guiding forces. Operators traced around a finished model of the final product and no real time material removal is carried out, therefore it is difficult for them to visualize what material has been removed. There is no evidence of a usable output generated.

Further research was carried out by Balasubramanium et al [79] on 5-axis milling. Again by allowing a human expert to trace around an object, information regarding tool orientation and position is captured. In this application the haptic model is represented by a point cloud and the tool by implicit equations, no real time material removal is carried out but areas of the model that have been touched by the tool are painted a different colour. The issue of operator induced noise introduced into logged data through hand jitter is highlighted and an approach mixing automatic path generation and operator defined tool access implemented to overcome this. Tool position and access is recorded as a series of vectors attached to each triangle of the tessellated image model.

Research into the rendering of realistic milling forces was undertaken by Yang and Chen [80]. This work focuses on the conveying of milling forces to the user through the haptic device. Milling forces are derived from a calculated material removal rate, machining power and a look up table containing empirical data of actual milling forces. Although this work derives a usable approach for re-creating cutting forces this type of realism may not be necessary in a planning application. This is highlighted in the requirements of creating a convincing VE (3.2) and the lessons learned from surgical planning (3.3.1) indicating abstract models may be sufficient.

Zhu et al [81] developed a volume-based free-form sculpting/milling application capable of outputting either the sculpted model as an STL file or the tool path in NC-code to generate a carving. Operators were able to sculpt a billet of material where the tool path was logged and converted into NC-code. The NC-code was validated by recreating the sculpted billet in NC simulation software. The same authors later refined and applied their work to pencil cut planning, aiding a user to find optimal tool orientations in a complex machining environment [82]; thus involving the user in the decision making process and capturing their knowledge with regard to operation sequencing, tool access and tool orientation.

A more comprehensive collection of tools was reported by Chen et al [83] where a virtual sculpting system was developed to provide an integrated product development platform which allows material to be milled from a block or for products to be reverse engineered. Stress and strain analysis could be conducted, allowing the operator to feel the stress and strain applied to an object. CNC tool path investigation could also be carried out with the aid of a haptic device for either machining or CMM inspection.

3.4.2 Haptic virtual reality and fixture planning

Haptic VR has also been applied to fixture planning by Liu et al [84]. Under the essential requirements of a process planning system (2.2) fixture planning is a sub section of defining the work holding requirements of a job. A haptic guided fixture load planning system was developed to allow the user to decide and then capture information required for the calculation of forces required to move, locate and secure a part into a fixture. This expertise was captured for later use in an automated manufacturing system enabling a robotic system to locate a part in a fixture with the correct loading force. This research aims to capture human knowledge in order to train an automated system but does not aim to aid a human fixture planner in carrying out a fixture planning task. Set up and tear down sequences and associated time and costs are not addressed. Interestingly there are many similarities between fixture and assembly planning, with both being a predominantly manual task that requires local expertise to perform effectively: however the limited literature available with respect to fixture planning highlights a significant knowledge gap in this area.

3.4.3 Haptic virtual reality and inspection planning

Haptic applications have also been developed that address quality through inspection planning, another essential process planning requirement. A system for virtual coordinate measuring machine (CMM) path planning was developed by Chen et al [85] aiding measurement point selection by allowing the operator to feel collisions between the product and probe tip. This was later extended to include path planning [86] where constraint planes and haptic snapping forces were implemented to support the operator in generating smooth paths quickly. Accessibility for the CMM probe was more closely scrutinized by Wang et al [87] where an improvement in collision detection was achieved by using a spatial occupancy test called "spatial run length encoding". This work was later extended to use STL files instead of the spatial occupancy models [88]. These applications demonstrate how a haptic VR environment intuitively aids the operator in developing metrology strategies whilst collecting their knowledge for later use.

3.4.4 Haptic virtual reality and training systems

Other systems that apply haptics and VR to promote knowledge exchange are training systems. Although the initial intention is for the trainee to gain information there is no reason why the information exchange cannot be bi-directional.

A milling simulator developed by Crison et al [89] used a proprietary haptic device as an abstract model of a milling machine with 2 degrees of freedom (DoF). The purpose was to create realistic feedback in order to allow an operator to explore and understand machining parameters in a safe environment. Visual, audio and haptic feedback was displayed as the operator carried out the machining task. A realistic 3-axis CNC trainer which included cutting sound, verbal input and feedback was developed by Wasfy et al [90]. The only haptic feedback mentioned was haptic gloves, although no detail was reported thus the emphasis is really non-haptic VR. However, both systems found the virtual training systems were able to enhance or create operator knowledge of milling in a safe and effective way.

3.5 Discussion of salient haptic VR literature relevant to process planning

A critical analysis of a process planning system's essential requirements (2.2) and two of the key desirable characteristics (2.3.2) was compared to the embedded functionality of relevant existing haptic virtual applications as illustrated in Table 4.

Table 4 Literature survey comparing salient haptic applications and ideal process planning system requirements.

	Commercial process planning approaches				Haptic virtual machining environments applicable to process planning							
	Traditional	CATIA	Creo	EdgeCAM	[79] Balasubramaniam et al	[80] Yang and Chen	[81] Zhu and Lee	[82] Zhu and Lee	[78] Chen and Tang	[89] Crison et al	[90][2] Wasfy et al	[83] Chen et al
Process planning essential requirements												
Drawing interpretation and material evaluation.	x	x	x	x								
Process selection and sequencing.	x											
Machine selection and operations sequencing.	x	x	x	x	x	x	x	x	x	x	x	x
Tooling selection.	x	x	x	x	x	x	x	x	x	x	x	x
Setting the process parameters.	x	x	x	x		x	x			x	x	x
Calculate machining times	x	x	x	x								
Determining the work holding requirements.	x	x	x	x							x	
Calculate set up time	x											
Selecting quality assurance methods.	x											x
Documenting the process plan.	x	x[3]	x[3]	x[3]								
Costing the plan.	x											
Process planning desirable characteristics specific to user												
Involve user in some part of the decision making process.	x	x	x	x	x	x	x	x	x	x	x	x
Include a user friendly interface.					x	x	x	x	X			X

Strength with which requirement/characteristic is met.	Weak		Strong

[2] This paper mentions an interface to haptic gloves but no further work regarding this is reported

[3] NC code primarily

It can be seen that haptic VR systems are being used to include planners in the decision making process and that these systems capture and in some limited cases document that expertise. However, there has been no attempt to create an integrated approach to a haptic-based process planning system covering all of the essential requirements. Such a system would require the functionality to produce a multi-process planning sequence or consider multiple functionality in a single operation such as set-up, tear-down and associated manufacturing time/cost calculations. Further there has been no attempt to formalize specialist knowledge captured during a haptic virtual machining simulation into a descriptive, easily understandable process sequence. Indeed only limited NC output has been produced in a very few cases and even then it must be kept in mind not all processes are NC based.

This research will address the gaps highlighted in Table 1 by showing that a haptic virtual process planning environment can be implemented which integrates the necessary process planning functionality as defined by the literature, whilst investigating if the application of a haptic VR interface addresses some of the desirable characteristics of CAPP systems highlighted in literature [9].

This builds on previous virtual reality research, contributing novel interaction and output as well as combining the relevant lessons learnt from previous work in virtual surgical planning, virtual assembly planning, and virtual machining. This will lead to the creation of an integrated virtual process planning system and demonstrates the incorporation of a new haptic technology paradigm not currently investigated in the field of CAPP.

3.6 Review of approaches to 'usability' evaluation within VR systems

In order for new technologies to gain mainstream adoption it is important that their benefits are clearly demonstrated. In spite of the work carried out in the field of process planning, no in depth work has been carried out with regard to the usability of such systems.

ISO 9241-11 with reference to Human Computer Interaction (HCI) defines usability as:

- '...the effectiveness, efficiency and satisfaction with which specified users can achieve specified goals in particular environments.'

The individual aspects of usability are further described by [91] who describe the following as:

- effectiveness: "...the intent as to which the intended goals of use of the overall system are achieved";

- efficiency: “...the resources such as time, money or mental effort that have to be expended to achieve the intended goals” ; and
- satisfaction: “...the extent to which the overall user finds the system acceptable.”

However, any assessment of a system's usability is highly dependent on its context of use [92]. The context is considered to include the user, the task and the environment [91]. Should any of these variables change, the context is considered to be different and the output of the usability assessment will be altered. A clear understanding of the system context is critical for system evaluations since it lays a firm foundation for the definition of the test and allows further comparable testing at a later stage.

Data acquired in usability testing can be objective or subjective [93]–[95]. Objective measures are more likely to be collected by quantitative data such as: measures of time, physiological responses or evaluation of results [96] and are suited to measuring a system's efficiency and effectiveness; subjective measures which consider the users’ perception or attitude towards the system can be collected by questionnaire, interview or observation capturing a user's satisfaction of using a system.

Hornbaek [96] reviews the use of questionnaires as part of a wider study and states that the measurement of usability questionnaires is in disarray. It was found that many HCI experts prefer to develop their own rather than use standardised questionnaires with little regard to previous work. The primary reason for this is to find specific information relating to the system they are developing, however, although this aids specific studies, it does not help comparative testing in a wider context. It is therefore important to include some form of standardised questionnaire if cross platform comparison is required. Some of the openly available standardised questionnaires are System Usability Scale (SUS), Software Usability Measurement Inventory (SUMI), Usefulness, Satisfaction and Ease of use (USE), Computer System Usability Questionnaire (CSUQ) and Post Study System Usability Questionnaire (PSSUQ). However only SUS and USE are suitable for any interface with the others being constrained to specific interfaces such as those of a computer [97]. The SUS questionnaire has fewer questions than the USE questionnaire and is widely used, known to be robust [97], yields reliable results across different sample sizes [98] and includes a measure of perceived learnability [99].

In [96] measures of efficiency being used were found to include input rate, usage patterns, communication effort, learning measures, mental effort and task completion time. Input rate measures the speed at which a user can input data, usage patterns measures how an operator uses the interface and can include key presses or measures of deviation from an optimal solution, communication effort is related to group work and measures the resources necessary to communicate, learning measures use changes in efficiency as an indicator of learning and mental effort measures the amount of mental effort required by the user during interaction. Task completion time (TCT) is a measure of how long it takes to complete the predefined task and is one of the more widely used methods for measuring task efficiency. However as most systems require motor and cognitive effort to achieve an end result [100] and it is suspected that the better information visualization of VR systems will reduce the mental effort required to produce a process plan both motor-physical and cognitive efficiency should be investigated. In the survey carried out by Hornbaek [96] the measurement of mental effort is predominantly measured by subjective means with the only objective measure reported being heart rate variability [101]. The issue with measuring heart rate variability is that it affects the context of the experiment, operators when using a system would not typically wear a heart rate monitor and the idea is to keep the context as close to that of real life as possible in order to get the most relevant data.

A variety of techniques have been used to measure the effectiveness of systems [96]. These include: expert assessment, binary task completion, accuracy, recall, completeness and quality of outcome. Expert assessment is the grading of the outcome of the system by an expert, binary task completion refers to the task being successfully completed or not, accuracy relates to the number of errors operators make whilst carrying out the task, recall measures how much information can be remembered by the operator after using the system, completeness relates to how well tasks are solved and quality of outcome aims to measure the quality of the work product.

A review of the most pertinent literature with regard to usability measures and haptic VR where SUS questionnaires have been implemented:

An investigation into the usability of a haptic system was investigated by Richter et al [102] where a driver inputs a number sequence into a haptic and non-haptic touch screen interface while driving in a virtual simulator. TCT was used to measure task efficiency, error rate for effectiveness and a SUS questionnaire for satisfaction. Pirker et al [103] measures the use of a touch enabled and classic television remote control. User perception is measured by SUS and AttrakDiff questionnaires, whilst efficiency was measured by TCT and effectiveness by task completion rate. The researchers investigated how users perceive the usability of the two interfaces i.e. what is the user experience and what is the relationship between the two? Rosenburg and Brave [104] evaluated the addition of force feedback on a user-interaction within a graphical user interface (GUI). Operators were required to press a button or select a menu item. TCT was measured and haptic feedback was found to have a positive impact on task efficiency. Shillito et al. [105] highlights that CAD packages due to their complex interfaces may stifle creativity so evaluates the use of a haptic based drawing system. In this investigation a SUS and NASA-TLX questionnaire were used and discussion and comments recorded. The NASA-TLX adds a measure of perceived workload to the subjective data collected. Lower scores achieved by the haptic system were attributed to the inability of users to select particular force constraints when required. Scali et al [106] compares a traditional 3D windows icon menu pointer (WIMP) interface to a 6DoF haptic interface in 3D Studio Max. Various configurations were implemented including haptic feedback, snapping forces and stereovision. SUS and NASA-TLX questionnaires were used and TCT measured. Findings found haptic and stereovision eased operation in a 3D environment, haptics lowered the perception of workload and snapping can reduce TCT. Whilst investigating the field of haptic assembly planning Lim et al [107] compared the use of a virtual haptic set up, HAMMS and a real world assembly task. An SUS questionnaire captured subjective data and the TCT measured to compare task efficiency. The haptic time was found to be approximately double the real world time of placing a peg in a hole. Comai and Mazza [108] investigated the usability of a haptic-enabled chemistry e-learning software system where participants used a haptic device to investigate the electric charge around a molecule. SUS and ASQ questionnaires were completed and talk aloud commentary recorded. The ASQ, a very short questionnaire provided information on the usability of the system for each task carried out whereas the SUS was carried out at the end of all tasks giving an assessment of the overall usability of the system for all tasks.

A summary of these usability evaluations is illustrated in Table 5. It can be seen that researchers have investigated the efficiency and effectiveness and satisfaction of use of haptic VR systems. However, with regard to efficiency no research has been carried out in deriving measures of cognitive or physical motor efficiency. With regard to effectiveness, researchers have investigated haptic applications but no specific work has been carried out with regard to the effectiveness of CAPP systems.

In addition to the formally recognised usability measures the analysis criteria in Table 5 have been further extended to identify if researchers followed a formal method of root cause analysis or included a measure of learning. A root cause analysis will aid the understanding of the level of usability identified. A measure of learning is included since some researchers believe a measure of learnability should be included in a usability study [109] and that learning or time required for training was identified as one of the reasons for the low uptake of CAPP in Chapter 1.

Table 5 illustrates that although some work has been carried out on haptic interfaces, no usability studies have been carried out which include the following:

- evaluate process planning systems, including CAPP;
- enable a cross platform comparison of such systems;
- include a formalised approach for root cause analysis; and
- measures of learnability, system efficiency, system effectiveness and user satisfaction.

These gaps will be addressed by this research.

Table 5 Summary of haptic VR usability studies (SUS questionnaire only)

Application	CAPP	Cross platform	Context defined	Satisfaction measured	Root cause analysis	Learnability	Effectiveness measured	Efficiency measured	
								General	Motor /Cognitive
[102] Richter et al	No	No	User not defined	Yes	No	No	Yes	Yes	No
[103] Pirker et al	No	No	No	Yes	No	No	Yes	Yes	No
[104] Rosenburg and Brave	No	No	No	No	No	No	No	Yes	No
[105] Shillito et al	No	No	Enviroment not defined	Yes	No	No	No	No	No
[106] Scali et al	No	No	User and environment not defined	Yes	No	No	No	Yes	No
[107] Lim et al	No	No	User and environment not defined	Yes	No	No	No	Yes	No
[108] Comai and Mazza	No	No	Environment not defined	Yes	No	No	No	No	No

3.7 Summary

It can be seen that haptic VR systems have been used in non-machining domains as an intuitive interface that promotes a better understanding of complex problems, facilitates the inclusion of the operator in decision making and, in a limited number of cases, captures and documents their expertise in a fashion very similar to those required by process planning i.e. virtual assembly. However, current research is fragmented with some of the functionality necessary to meet the essential requirements for process planning being carried out in isolation. A key gap is that none of these separate areas have yet been incorporated into an integrated suite of functions, applied to a process planning environment or tested. Further, another finding is that no serious attention has been paid to system usability in order to thoroughly evaluate how new solutions such as that proposed actually compare and perform against current practice or current solutions. It is this type of evaluation which will confirm if the work carried out in this research does in fact bring benefits over existing approaches.

Therefore, from the literature, key gaps in current process planning knowledge are:

- No investigation or development of a fully integrated haptic-based process planning system has been carried out.
- No haptic VR-based systems exist that integrate the full functionality to meet all of a process planning system's essential requirements.
- No process planning usability methodology is available to evaluate and/or compare process planning systems.

Chapter 4 HAPP research philosophy and plan

4.1 Introduction

In this chapter different research approaches are discussed along with different software development models. These provide a grounding to enable the most relevant research and development approach to be selected. The phases of the chosen approach are highlighted and an overview given of the research plan to be implemented.

4.2 Research approaches

There are several fundamental approaches that can be taken during a research project [110]. These may include deductive reasoning where a hypothesis is set out as a theory with a supporting method to prove or disprove it, inductive reasoning where a method is set out and a theory is developed from observations taken during the experiment or abductive reasoning which is a combination of the two. In abductive reasoning the initial hypothesis is a ‘best guess’ but this may evolve as the experiment is carried out and results analysed. Although deductive reasoning is rigorous it sometimes fails to capture the reasons as to why a theory is the way it is. This is why inductive reasoning was developed; it does not attempt to conclude if something is true or false but attaches a cogent reason as to why it is as it is. Abductive reasoning includes both types of reasoning with objective data providing evidence of the state of the system and subjective evidence providing a deeper understanding of why that is. In this research an abductive approach was taken since it was felt deductive reasoning would not provide sufficient information for further development and inductive reasoning would not provide information in a means that would allow an easy comparison between different solutions. An initial hypothesis was stated and a method defined to evaluate it; this was also supported by observational and interview based data to try and ascertain reasons behind the results. This approach not only allowed a rigorous evaluation of the results but also the capture of relevant information to enable future development. Tightly linked into this approach is the software development strategy selected. It was important that the software development methodology allowed the system to be iteratively developed as a better understanding of the system benefits was obtained and the underlying reasons discovered.

4.3 Software development methodologies

There are many different software development methodologies available to guide and control the process of delivering software projects. Each methodology has its own strengths and weaknesses, often practitioners implement their own approach selecting the most relevant part from different systems. Some of the fundamental approaches [111] are: the Waterfall Model, the Prototyping Model and the Iterative and Incremental Model. These are defined as follows:

- Waterfall Model: a project is divided into sequential phases; these may include requirements analysis, design, implementation, testing and installation. The advantage of this method is it enforces a disciplined approach and ensures requirements are clearly defined at the start. The disadvantage is it may not be possible to clearly define the requirements at the start.
- Prototyping Model: a series of prototypes are developed and evaluated with the close involvement of the client. The advantages are a reduction in the risk of failure and a close working relationship between development team and client. The disadvantage is it can be expensive as prototype costs are normally absorbed by the developer and the process can be slow due to client involvement.
- Iterative and Incremental Model: This is carried out as a series of mini-waterfalls. A system is developed through repeated cycles with each new cycle taking advantage of information learned in the previous cycles. The advantage of this approach is that the software is generally easier to test and debug than other systems as the changes between iterations are relatively small: however, the disadvantage is that problems related to the system architecture may occur later on due to issues that were not originally foreseen.

The waterfall method does not work well with this type of research approach since all the requirements are required to be known at the beginning of the project. The prototyping model, although more suitable, requires new prototypes at each stage which is quite time consuming.

The iterative and incremental approach is considered to be the best fit for the selected research approach. This approach fits well with abductive research because in a similar fashion, initially a best guess system is defined, which is then developed and evaluated in order to assess if the initial requirements were attained and to capture a deeper understanding of how well they were achieved. This evaluation leads to discoveries, which then define the requirements for the next cycle of development; thus abductive reasoning is applied at each iteration.

An iterative and incremental approach consists of four fundamental phases: (i) requirements capture, (ii) analysis design and coding, (iii) testing and (iv) evaluation. These are iterated as illustrated in Figure 6.

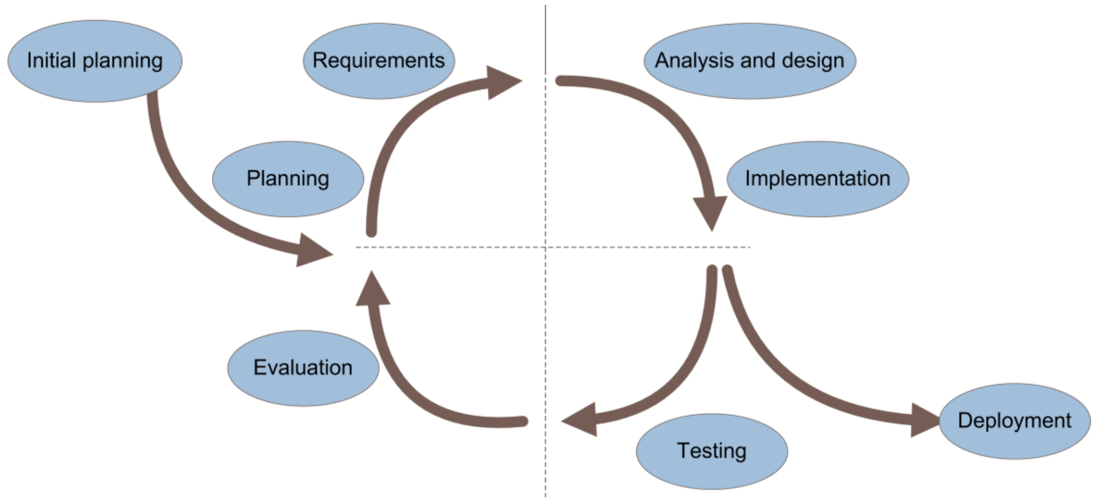


Figure 6 An iterative and incremental development cycle

4.3.1 Requirements

The requirements define the system behaviour. The requirements of this system are to provide a haptic VR application that can simulate sufficient process planning tasks within a machining environment to test the hypothesis that haptic VR can provide a useable process planning system.

4.3.2 Analysis, design and coding

An object orientated software development will be implemented in C++. This will facilitate modular and scalable software development.

4.3.3 Testing

Testing concerns the internal aspects of the software ensuring it functions properly, this and debugging will be carried out as an ongoing part of the system development.

4.3.4 Evaluation

Evaluation is the phase that checks the developed application conforms to the customers' requirements. It can apply to reliability, maintainability, portability, functionality or usability [112]. In this case the usability of the system will be evaluated, measuring the satisfaction of use, efficiency and effectiveness. These three measures will be captured as subjective and objective data ensuring opinion is supported by fact. A systematic approach is necessary to collect these data to ensure it is directly comparable between development phases and other process planning systems; with no other factors skewing the results. Furthermore, to carry out an initial evaluation it is necessary to compare the new approach to an approach that is already widely used and covers all the aspects of an ideal process planning system as defined by the literature. In this case only one exists, namely traditional process planning because it was found to be the only approach meeting this requirement.

4.4 HAPP System development and implementation

Three iterations of HAPP system development were planned namely pre-pilot, pilot and industrial studies. These are illustrated in Figure 8.

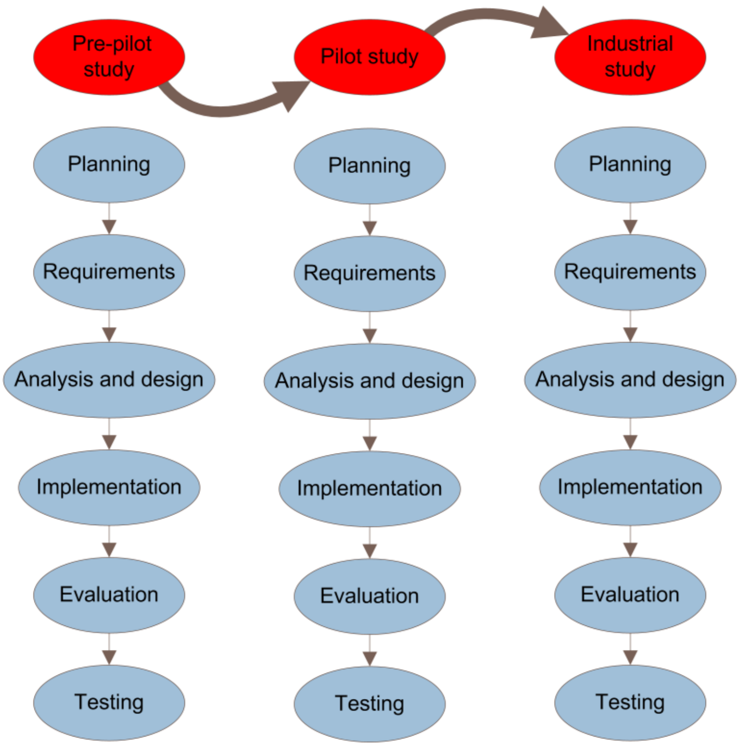


Figure 7 HAPP System development

4.4.1 Iteration 1: Pre-pilot study HAPP implementation and testing

During the first iteration the initial software application testing will be carried out using a few participants. No particular skills or process planning knowledge is required. The intention is an initial evaluation of the usability of such an interface for simulating the machining of metal parts. An analysis of the usability evaluation method will also be carried out with a view to improving the evaluation of the next version of the system. At the finish of this phase it is anticipated that research objective 1 will be evaluated.

4.4.2 Iteration 2: Pilot study HAPP implementation and testing

The second iteration will apply a more clearly defined experimental set up and method using a sample group of planners of mixed experience. A cross platform systematic approach for the evaluation of usability developed as a part of this work will be applied to benchmark a traditional process planning environment against the HAPP system; allowing an evaluation and comparison of the two systems. After the systems are compared the evaluation method will itself be analysed and further developments identified enabling a more comprehensive analysis of the HAPP process planning system. The intention is to address research objective 3, enabling a cross comparison of two process planning systems and answering research question 3 revealing how they compare with regard to system usability, efficiency and effectiveness.

4.4.3 Iteration 3: Industrial study HAPP implementation and testing

In the third iteration improvements identified from iteration 2 will be made to both the HAPP system and process planning evaluation method with usability of the system quantified and formalised as a contribution to knowledge. Here research question 3 and objective 3 will be further addressed along with research objective 2 and research questions 1 and 2 when completed. This should allow the aim and research hypothesis of this work to be answered.

4.5 Summary

The combination of an abductive research approach and an iterative and incremental development methodology for software development was chosen. This will allow the cyclical development and testing of the HAPP process planning system and the evaluation of the research aim, questions, objectives and hypothesis, as well as capturing a deeper level of understanding of the system. Three iterations of the system are planned: a pre-pilot, a pilot and industrial study with a mixture of subjective and objective data collected for analysis. The data collected will allow a usability analysis to be undertaken which will provide a comparison of the process planning system developed with the triangulation of data revealing how the system performed, helping identify further developments for the next iteration and further work.

Chapter 5 Initial HAPP system design and pre-pilot study

5.1 Introduction

This chapter discusses the initial HAPP system design with the initial system specification derived from the literature and discussions with experts in manufacturing companies. An introduction is given into the system requirements followed by a more detailed description of the component parts and the rationale behind their selection. The chapter closes with a description of the system implementation and initial testing in the form of a pre-pilot study.

5.2 HAPP requirements and specification

The goal of HAPP is to provide a practical and usable application for process planning. Typically process planning is a desk-based activity carried out within an office environment, therefore HAPP should fit comfortably into this environment. It should consist of commercially available hardware including a conventional PC and monitor set up and haptic device. The haptic device should be desk mounted and allow for ergonomic hand operation; primarily kinematic operations to manipulate objects and simulate machining tasks. HAPP should allow high interactive rates and be compatible with selected model types and be built from open source libraries to allow for future developments. The system specification is illustrated in Table 6 with regard to the previous defined process planning sub-categories.

Table 6 HAPP version 1 system specification

	HAPP	Description of how HAPP meets specification.
Process planning essential requirements		
Drawing interpretation and material evaluation.		
Process selection and sequencing.	x	The operator will be able to select either a centre drill or 2.5D milling machine in any order they choose.
Machine selection and operations sequencing.	x	The operator will be able to manipulate the billet and cutting tools to carry out cutting sequences in any order they choose with the haptic device
Tooling selection.	x	A 5mm drill, 10mm drill and16mm slot will be included. Tool access can be verified before cutting sequence is started.
Setting the process parameters.	x	Process parameters will be automatically included from set values in the Machinery handbook.
Calculate machining times	x	Times will be calculated from standard equations.
Determining the work holding requirements.	x	A machine vice and clamp set will be included to enable the operator to plan the set up before machining. These will be manipulated through the haptic device.
Calculate set up time	x	The set up time will be calculated for the set up simulation.
Selecting quality assurance methods.	x	A virtual CMM probe will be included to measure material removed.
Documenting the process plan.	x	Process plans as described in [3] [5] will be generated automatically after the planner has finished simulating the machining sequence.
Costing the plan.	x	A cost is automatically generated with the process plan based on an hourly rate multiplied by the set up and machining times.
Process planning desirable characteristics specific to user		
Involve user in some part of the decision making process	x	All processes are carried out by an operator and specialist knowledge will be unobtrusively logged.
Include a user friendly interface	x	A haptic VR interface will be implemented.

5.3 Initial HAPP Architecture

A description of the HAPP architecture in terms of hardware and software follows:

5.3.1 Hardware:

The SensAble Phantom Omni was chosen as a haptic input device as it is an active, open control loop, impedance-based haptic device, capable of 6DoF input with 3DoF feedback. It suits the initial requirements of being desk mounted, fits the haptic characteristics of the human hand, is commercially available, reasonably priced, provides kinaesthetic interaction, can produce tactile feedback and is sufficient to simulate the machining processes modelled in this research. This device was used in combination with a desktop PC (Intel Core i5 processor) with an nVidia Quadro FX 580 GPU and a standard monitor.

5.3.2 Software:

Based on information obtained from game engine design [113] and existing haptic assembly planning systems [73] the system software was created based on six constituent parts, with each described in more detail in this section:

- a graphical renderer ;
- physical modelling;
- haptic modelling;
- material removal;
- data logging;
- a plan parser ;

These are now covered in turn.

5.3.2.1 Graphical renderer

Before the graphics can be rendered on the display they must first be modelled [114]. CAD systems typically use surface representation models that are often a mixture of different parametric surfaces. As CAPP is closely linked to CAD it is important that the information interface between the two is compatible. A brief overview of different models is demonstrated in Figure 8. In general model types can be separated into two distinct groups: surface representation and volume representation. Surface representations appear solid but are actually hollow whereas volumetric representations are actually solid, having a defined inside and outside. CAD systems use surface representation models because they have lower memory requirements which means they can be manipulated more quickly within a software application and are more accurate for modelling curved surfaces. However, since many CAD systems implement slightly different approaches for parametric surfaces as shown in Figure 8, cross compatibility can be a problem. For this reason a polygon mesh format is commonly used and .STL has become the de facto common standard. The main limitation to this format is that it is not quite as effective at modelling compound curves as in parametric approaches. As a polygon mesh is a common standard and sufficiently accurate for the modelling purposes required it has been chosen as the model type for HAPP.

Rendering is the process of taking the 3D model or scene and transforming it into a 2D image on the display. This is achieved by passing the model along the graphics pipeline. Images can be pre-rendered, as is the case with animated films where considerable time is spent creating images in advance or rendered at interactive rates, as is the case in video games. For this application it is critical that the rendering process is achievable at interactive rates to allow operators to receive immediate feedback from their actions; therefore, libraries that apply pre-rendering techniques are not applicable.

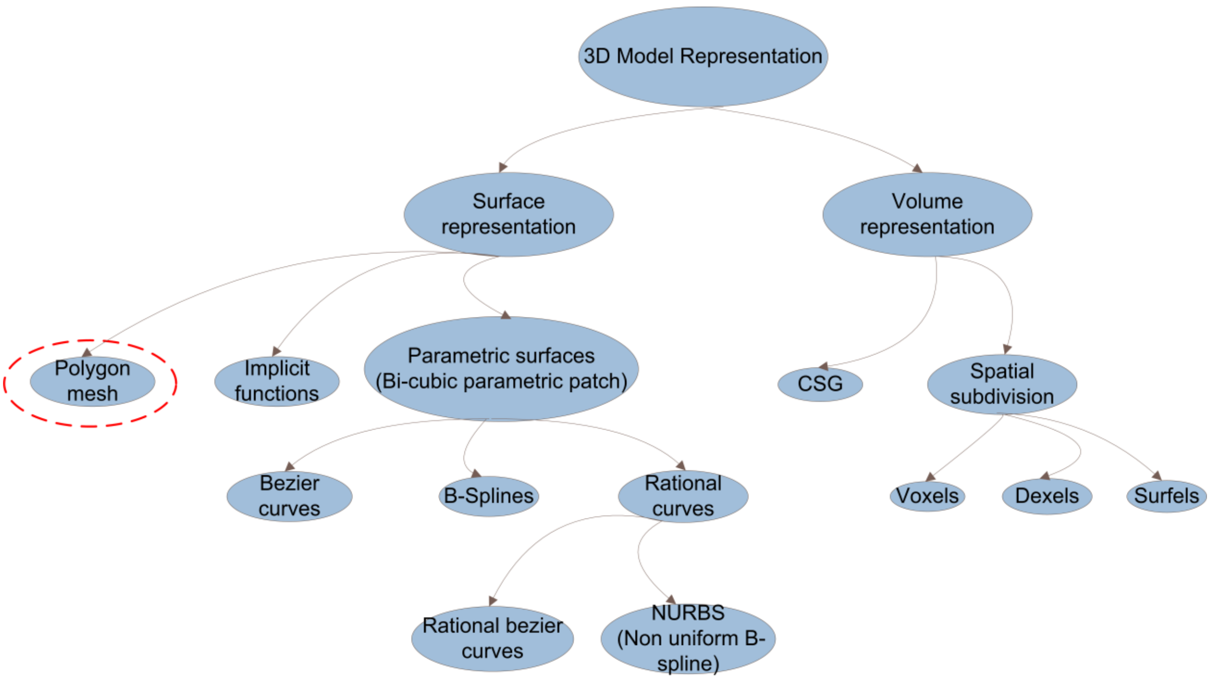


Figure 8 3D Model Representation derived from [114] and extended to include dexels and surfels.

In the graphics pipeline images are clipped, projection and viewport transformations applied and lighting, shading and textures added before the final image is displayed. Clipping removes objects that do not fall within the viewing frustum, i.e. the field of view that will appear on the screen. The projection transformation modifies the image with regard to the type of projection applied; if perspective projection is used objects in the distance are made to appear smaller. If orthographic projection is used then the objects remain the same size. The viewport transformation modifies the image to fit the display size at which it is to be finally rendered.

In order to add features such as texture, lighting and shading to the final images there are many different approaches all with differing levels of realism and efficiency. These can be broadly generalised under four categories: rasterization, ray casting, ray tracing and radiosity [114]. Rasterization was chosen since this is the most commonly used approach in which interactive rates are required as opposed to the other methods which evaluate a scene pixel by pixel. Rasterization groups sections of the models into higher level groups called primitives such that when the scene is updated only the pixels in affected primitives are modified.

There are several commonly used Application Programming Interfaces (APIs) for rendering graphics in 2D or 3D and one of the most commonly used is the OpenGL API [115]. OpenGL implements a rasterization algorithm; however, as this is purely a rendering API and does not provide any further functionality, such as model loading, rendering analysis tools or GUI elements a middleware layer was selected, Open Scene Graph (OSG) [116]. OSG is open source and implements a "hierarchical tree data structure" [117] that organises the geometry into a more efficient way for rendering, improving the system's ability to meet the requirement of achieving interactive rates.

5.3.2.2 Physical modelling

Physical models are abstract models of the scene objects that capture details of weight and surface friction with a view to recreating how the objects would move and interact with other objects in the virtual world as they would in the real world. A physics kernel that carries out this task typically consists of two constituent parts [118]: collision detection and collision response. Kernels are available which model soft and rigid bodies but due to the nature of the HAPP application, which is simulating machining, only the functionality for modelling rigid bodies is required.

The first task of the physics kernel is to model the object's movement. The classic approach is the implicit integration of rigid body dynamics where Newton-Euler equations are used to describe the combined translational and rotational dynamics of the tool. Time stepping techniques are then implemented in order to calculate velocity and position updates. After the objects have been set in motion the physics kernel checks if any objects collide. Collision detection is the monitoring of objects within a scene to detect if they intersect; there are generally two approaches used; discretely where object positions are checked at specific time intervals or continuously where the trajectories of the objects are calculated in advance. Collisions are normally detected after penetration has occurred in discrete systems (posteriori) whereas in continuous collision detection no penetration takes place (priori). Collision detection algorithms may be required to collect data regarding the point of contact, time of impact, number of points of contact (contact manifold) and depth of penetration.

Since collision detection is very processor intensive, a collision detection pipeline was established by [119] with collisions being processed at lower levels of granularity as more information is required. The initial phase, categorised as the broad phase, attempts to reduce the number of objects in the scene to pairs of objects likely to collide whilst a secondary stage, the narrow phase checks, those pairs in more detail. A graphical representation of collision detection algorithms derived from previously mentioned surveys [120], [121] and [122] is shown in Figure 9 and separated into broad and narrow phase techniques.

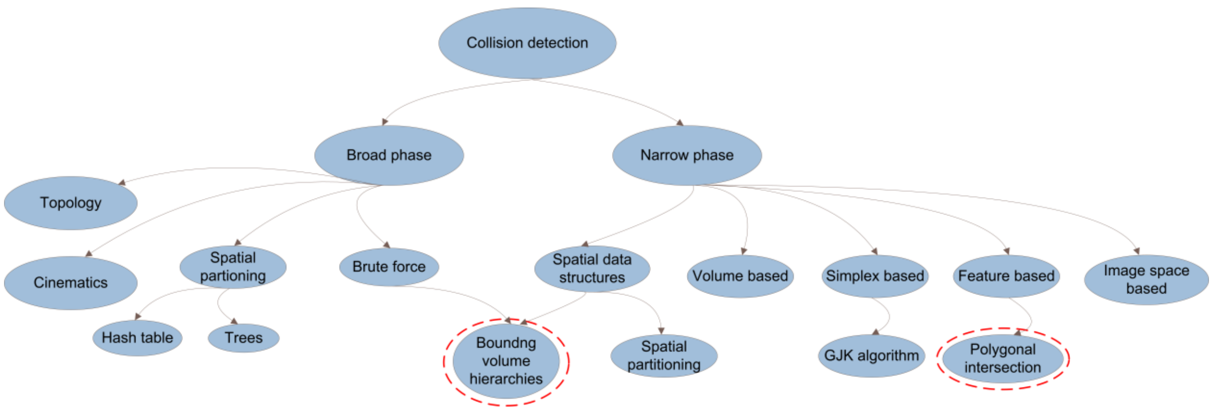


Figure 9 Collision Detection Algorithms derived from [120], [121] and [122]

The collision response generates forces based on the input of the collision detection module. Contact phenomena that affect the forces generated include reaction and friction. Reaction includes the amount of kinetic energy retained after the collision and is related to the elasticity of the bodies where friction is the force that impedes the sliding motion against each body due to microstructure imperfections. Collision response forces can either be calculated or generated from measured data. Measured data allows the inclusion of realistic data but is constrained to a specific measurable context whereas a calculated collision response attempts to generate the forces based on the information it receives. There are several methods that have been implemented to calculate collision response [123]: the projection based method which controls the position of an object; the penalty based method which controls the acceleration of an object and impulse based dynamics which controls the velocity of the objects.

One of the commonly used free, open source, physics modelling kernels that meets the physical modelling requirements of HAPP is ODE [124]. ODE is compatible with the polygon meshes, suitable for rigid bodies and includes an integrated collision detection library as well as collision response engine. The collision detection engine included is OPCODE, although an interface is provided to enable a different collision detection library to be used if required. APIs within OPCODE allow the use of spatial partitioning to speed up the broad phase aspect of the collision detection if required: although in this case, due to the small number of objects in the current application, no broad phase optimisation is implemented. A simple brute force approach taken where an Axis Aligned Bounding Box (AABB) [125] for each object is checked for overlap with an efficiency of $O(n^2)$ where O = operations and n = number of elements. The narrow phase is based on a dynamic intersection test for points on potential colliding pairs passed along the collision pipeline from the broad phase check.

5.3.2.3 Haptic rendering

The primary requirement of the haptic rendering is to provide kinematic feedback to the haptic device at interactive rates whilst manipulating objects within the scene. Haptic rendering is the creation of haptic forces at the haptic interface. Current methodologies can be classified as direct rendering and simulation-based rendering. These are illustrated in Figure 10 with a virtual tool which takes the form of a drill bit or other type of cutting tool and the billet which is the raw material ready to be machined. In direct rendering the configuration of the haptic device is assigned directly to the virtual tool. Collision detection is carried out between the tool and the virtual environment and collision response forces are calculated as a function of penetration depth or object separation using penalty based methods, with the resulting force passed directly back to the haptic device. This approach is simple to implement but penetration values may be quite large and perceptible. If the force update rate drops significantly pop-through may occur and force discontinuity or device instability may be felt. In simulation-based rendering the forces and torques are applied by the haptic device to a virtual tool where this is the avatar of the haptic device within the virtual scene. As forces act on the avatar its position and attitude are calculated and returned to the haptic device through a virtual coupling. The virtual coupling was developed in order to reduce the instability to which direct rendering algorithms are prone. This approach is used in the god object [126] and virtual proxy algorithms [127] for 3DOF haptic devices. The advantage is improved device stability. The disadvantage is when the update rate of the haptic algorithm is too slow there will be a loss of stiffness through a reduced rendering impedance, i.e. loss of quality.

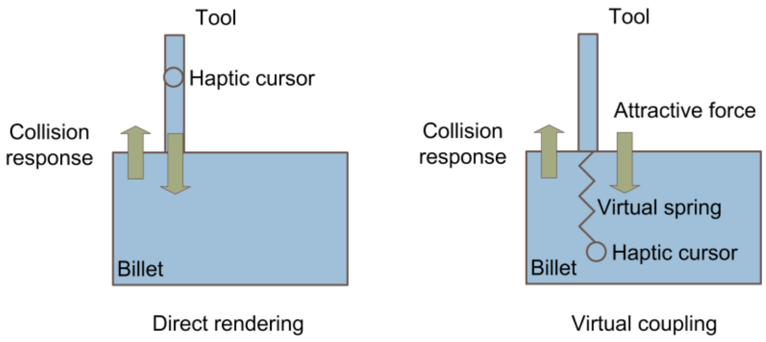


Figure 10 Haptic rendering methods

There are several haptic libraries available such as Chai3D [128] which is open source and OpenHaptics [129] which is free to use under an academic license. A brief review of some of the libraries is given at [130]. In this review OpenHaptics is described as: "...a proprietary haptics library developed by SensAble Technologies. OpenHaptics uses a point proxy based approach (implementing a virtual coupling) and provides a stable haptic feedback. It is however not very extendable in terms of user defined surfaces and only works with haptics from SensAble Technologies." HAPP uses OpenHaptics because it is compatible with the hardware selected and, as the review also states, is a robust and fast haptic library.

Openhaptics provides three layers of APIs, each allowing a lower level access to functionality but subsequently requiring more time for implementation. These are listed below in descending order of ease of use.

- Quickhaptics;
- HLAPI;
- HDAPI.

HAPP uses the HDAPI libraries as it was felt that they would provide maximum flexibility during system development.

5.3.2.4 Material removal

HAPP is required to perform material removal operations with regard to drilling and milling. Thus models need to be modified in real time with immediate feedback to give the operator an increased sense of immersion, which in turn should improve the operator's cognition and perception.

Current approaches for geometric modification include Boolean operations or model deformation. Boolean operations are well documented, particularly with respect to

Constructive Solid Geometry (CSG) [131]; however, due to the model complexity of surface model representations it is difficult to achieve interactive rates. Model deformation approaches have been applied to various surface representations be they polygon mesh [132], parametric models [133] or blobby models which are isosurfaces defined by an implicit equation [134]. However, these often require complicated processes to enable mesh modification, such as the generation of finer meshes [132] and the results may not be as accurate as Boolean operations at interactive rates. One approach to overcoming the speed issue for Boolean operations on surface models was developed by Goldfeather et al [135] who used the graphics hardware. This approach only modifies the visual representation of the model but not the geometry itself, which is required for haptic interaction.

HAPP takes a dual approach within the material removal algorithm to enable real time rendering with minimum impact on the haptic and graphic frame rate during the cutting sequence. It is important that the image is updated in real time so that the operator can see the material being removed but not the object geometry. The object geometry is only updated to allow the operator to feel the shape or position of objects through the haptic device. During cutting the operator does not need to feel the shape or position of objects, only the cutting forces. For this reason, during the cutting sequence only image representations of the models are updated in real time with the object geometry updated later between material removal sequences in delayed time (Figure 11).

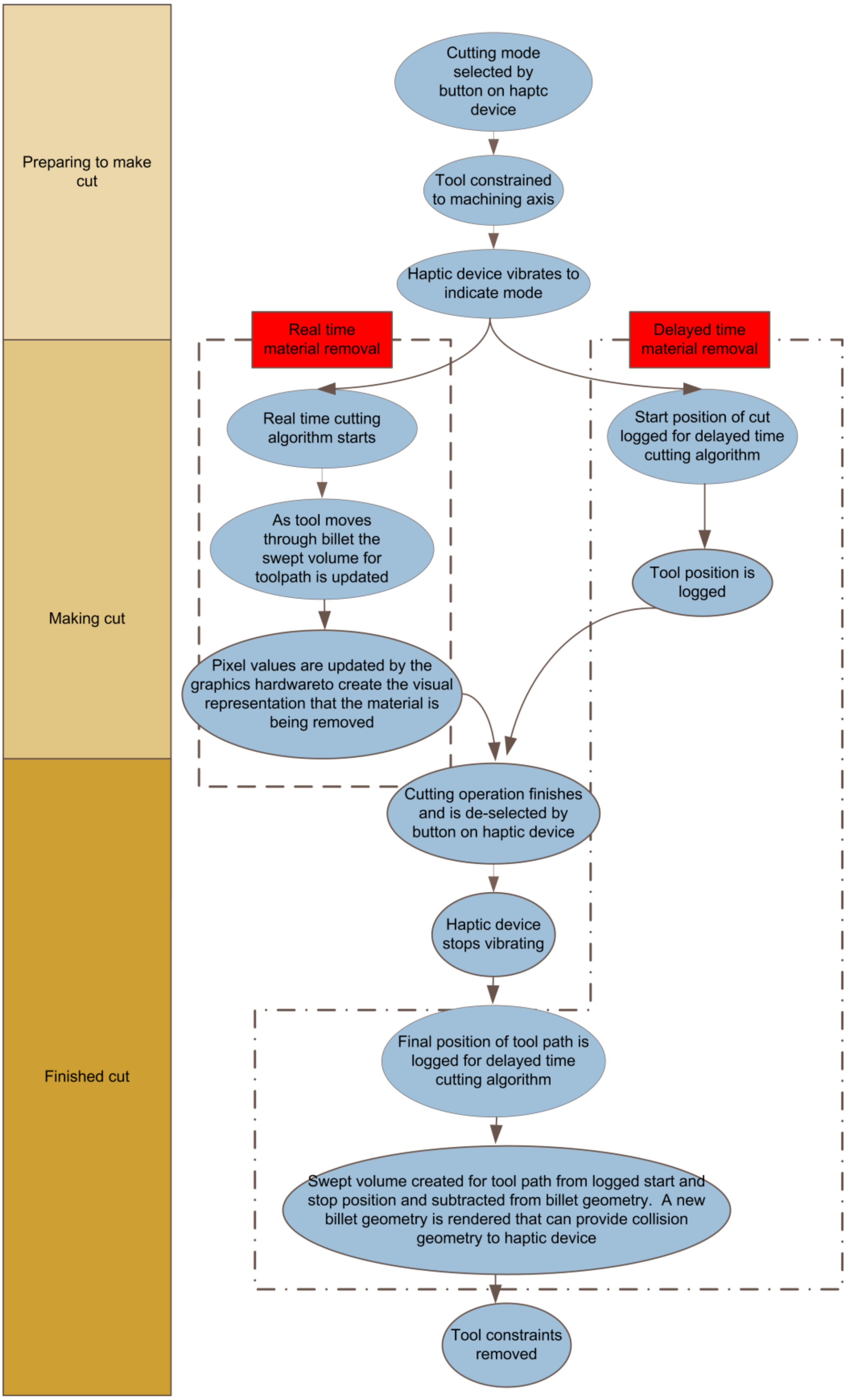


Figure 11 Material removal algorithm

Real time material removal: With regard to real time material removal, drilling operations are trivial because the drill obscures the material removed until it is withdrawn from the billet, thus no real time model modification is necessary; however, this is not the case for milling. As the milling tool does not obscure the material removed, a means of visualizing a newly modified billet in real time is required. This is achieved by an image-based Boolean operation [136]. Since this type of operation only modifies pixel values but not the actual model geometry, it is very fast and real time render speeds can be obtained. HAPP implements the Z-fail algorithm [137], the stencil buffer and multiple render passes. After each iteration through the graphic render loop a new swept volume is calculated based on the tool start position and the tool current position. The tool geometry is constructed in such a way that the left and right-sided vertices are easily separated into component halves as illustrated in Figure 12 and Figure 13. This swept volume is then subtracted from the billet model. Since a new swept volume is being calculated and subtracted from the billet volume for each pass through the render loop a visual representation of material being removed in real time is presented.

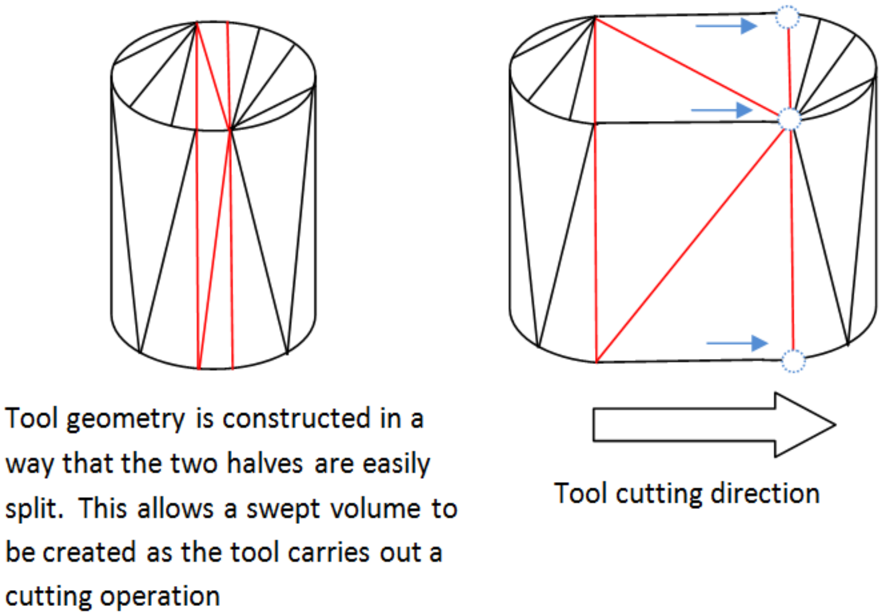


Figure 12 Tool geometry to enable swept volume generation during milling

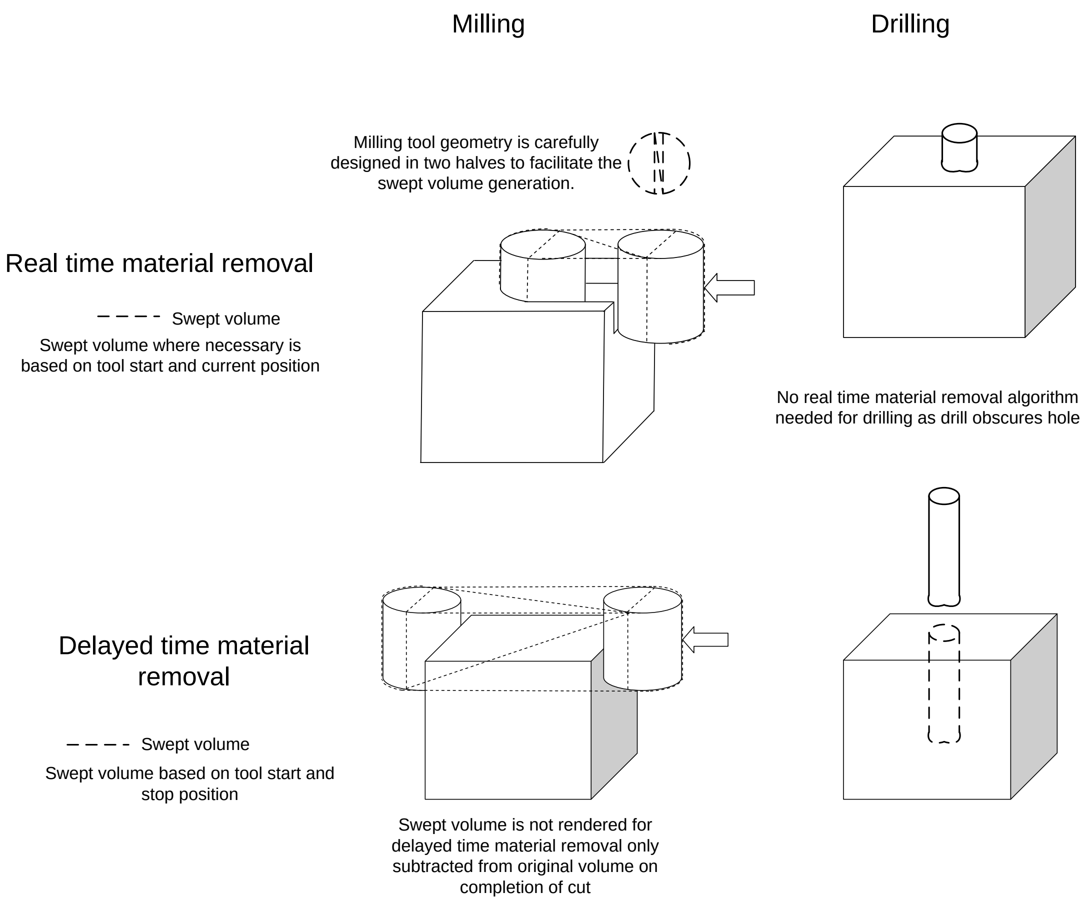


Figure 13 Swept volume illustrations.

Delayed time material removal: For drilling, the drill geometry is merely translated to the maximum logged drill depth before the Boolean operation is carried out. For milling the final swept volume as calculated in the real time material removal operation is subtracted from the billet volume. OSGModelling [138] is used for this task. OSGModelling is open source, facilitates boolean operations on polygon meshes and is fully compatible with OSG. In both cases the tool or swept volume geometry is passed to OSGModelling, which subtracts the swept volume from the billet volume. The geometry modification occurs once per cutting sequence after the cutting operation is finished and the tool is withdrawn from the billet. Finally a new physics model is generated for the modified geometry.

OsgModelling uses Binary Space Partition (BSP) trees for spatial indexing of the polygon models and bounding boxes to improve the speed of the Boolean operations. Initially BSP structures of tool and billet models are created. The triangles that make up the model are partitioned into lists and the software checks a sample of faces in the model to find the initial partition plane that produces the most balanced tree, i.e. a tree with a similar amount of positive and negative children. Once the optimal partition plane is selected each face is defined as a positive face, negative face, cross face or coincident face with regard to the partition face and placed in the positive or negative lists (Figure 14). Cross face means the triangle straddles the partition plane so is split until only positive, negative and coincident faces exist within the tree structure.

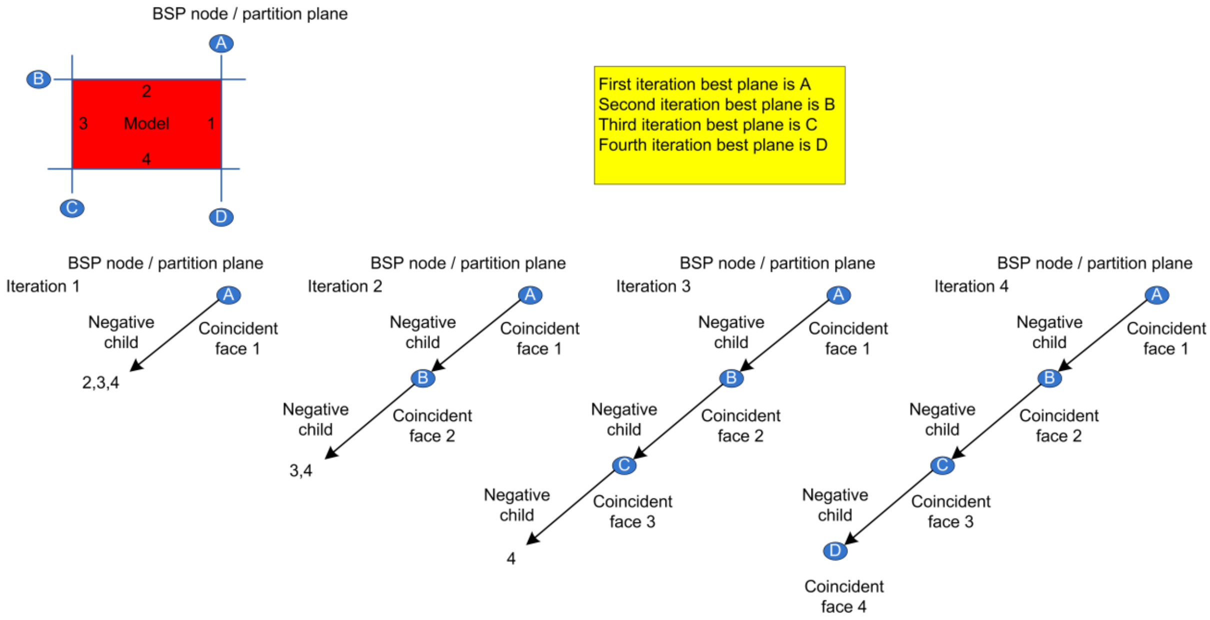


Figure 14 BSP tree build illustration

For a rectangular polyhedron the BSP tree is very inefficient as illustrated in Figure 14, which demonstrates a fully built tree at iteration 4 with only negative children: However, as models become more complex the tree will become more balanced with similar numbers of positive and negative children. Once the BSP tree has been built, a bounding box is calculated for the model for later broadphase collision detection during Boolean operations.

Boolean operations that can be carried out on polyhedra consist of intersection, union, difference and exclusive-or: intersection is the area that is in both polyhedra, union is the area combined by both polyhedra added together, difference is the area contained in the first polyhedron but not the second and exclusive-or is the area(s) of the polyhedra that do not intersect (Figure 15).

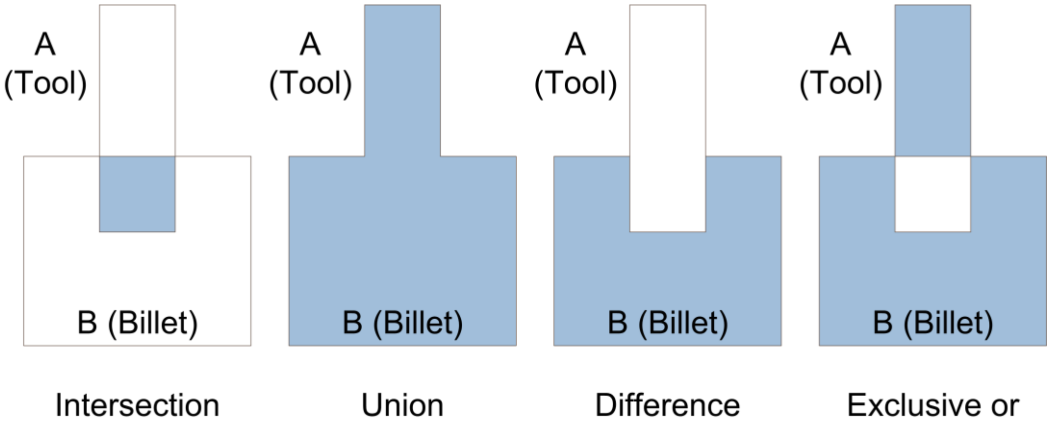


Figure 15 Boolean operations

All of these operations can be carried out by combinations of negation and intersection [139]. The negation of a polyhedron is the area that is not inside it. Therefore for polyhedra A and B:

- negation of A: $\neg A$;
- intersection of A and B: $A \cap B$;
- union of A and B: $A \cup B = \neg(\neg A \cap \neg B)$;
- difference of A and B: $A \setminus B = A \cap \neg B$;
- exclusive-or of A and B: $A \oplus B = \neg((\neg(A \cap \neg B)) \cap (\neg(B \cap \neg A)))$.

As the primary interest in HAPP is material removal the difference operation will be the main focus (Figure 16). The first step is to negate the tool volume; this is achieved in OSGModelling by flipping the triangle normal, followed by checking for intersections between the billet and the negated tool volume. A recursive check for each triangle against its opposing volume is run to define if it is intersecting or not. Once the list of intersecting triangles is complete they are then rendered to the screen revealing the newly modified geometry. To speed up the algorithm an initial check using bounding boxes is carried out before checking all the individual faces.

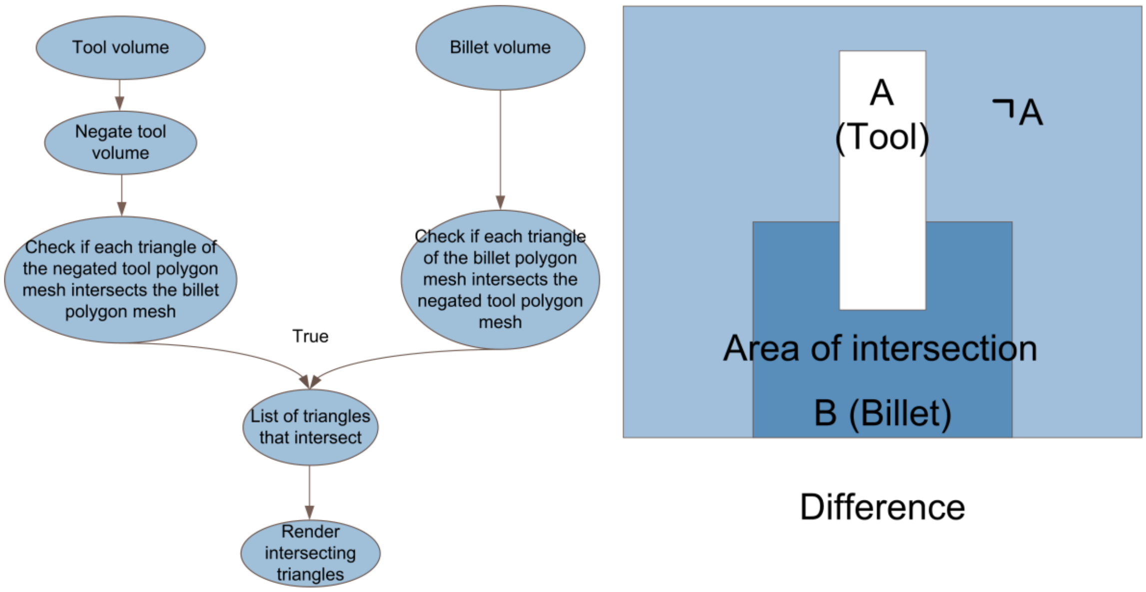


Figure 16 Difference operation for material removal

5.3.2.5 Data logging

To capture the interactions between the virtual objects and the process planner the OpenHaptic libraries are used to chronologically log all information regarding the speed, position and applied force at the haptic cursor. This allows the tool movements and associated status to be logged in the background throughout the process with a timestamp; the raw data are recorded in a .txt file (Figure 17).

Time(s)	Tool	Tool State	L_Force(x)	L_Force(y)	L_Force(z)	L_Position(x)	L_Position(y)	L_Position(z)
39	5mm drill	OFF	0.1181	0.4909	0.07674	12.51	-20.04	0.003492
39	5mm drill	OFF	0.1181	0.4909	0.07673	12.51	-20.04	0.003492
39	Stop Manipulation							
0	Start Manipulation							
0	5mm drill	ON	0	0.04129	0	12.51	-20.04	0.003492
0	5mm drill	ON	-5.76E-05	-0.2853	0.008751	12.51	-20.04	7.503
0	5mm drill	ON	-4.76E-08	0.1367	0.09855	12.51	-20.04	7.503
0	5mm drill	ON	1.39E-05	0.2561	0.09644	12.51	-20.04	7.503
0	5mm drill	ON	2.77E-05	0.5972	0.09434	12.51	-20.04	7.503
0	5mm drill	ON	0.000184	0.898	0.07059	12.51	-20.04	7.503

Figure 17 Sample of logged raw data

5.3.2.6 Plan parser

In order to formalize the logged information the plan parser filters this in real time and derives and adds in extra information where necessary to complete a process plan. An inference engine is used to calculate the derived information where machining times are calculated using standard machine time calculation formulae [5] (Figure 18) and the logged cutting distance of the tool. Process parameters such as feeds and speeds are drawn from the Machinery's

Handbook [140] based on tool and billet material. Set up times included in the plan are generated from empirical measures triggered by the haptic movement of the objects and fixtures. If required fixture plans and associated costs can also be generated, separately.

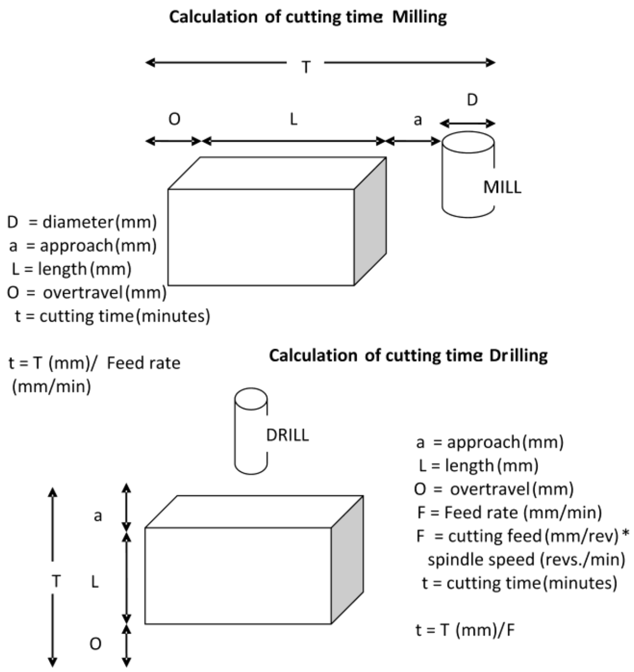


Figure 18 Machining time calculation

The process plan includes:

- A route list, which details an operation description and selected work station.
- An operations list where the process parameters and machining times are defined for each cutting sequence.
- A tool list listing the tool requirements for the complete job and their associated operations.
- Time/cost estimation, including set up and machining time.

5.4 System integration

To create the virtual world objects a visual and physical representation is required. The physical model is derived from the graphical model loaded by the user (Figure 19, ①) at the beginning of a planning simulation. Objects are manipulated in the virtual environment using the haptic device (Figure 19, ②) which allows billets to be placed on the worktable at the appropriate position and clamps to be moved to hold it in place. When machining takes place the visual representation of the geometry is modified and then used to update the physical model (Figure 19, ③). All interactions between the operator and virtual world are logged with a time stamp which is parsed into the process plan (Figure 19, ④).

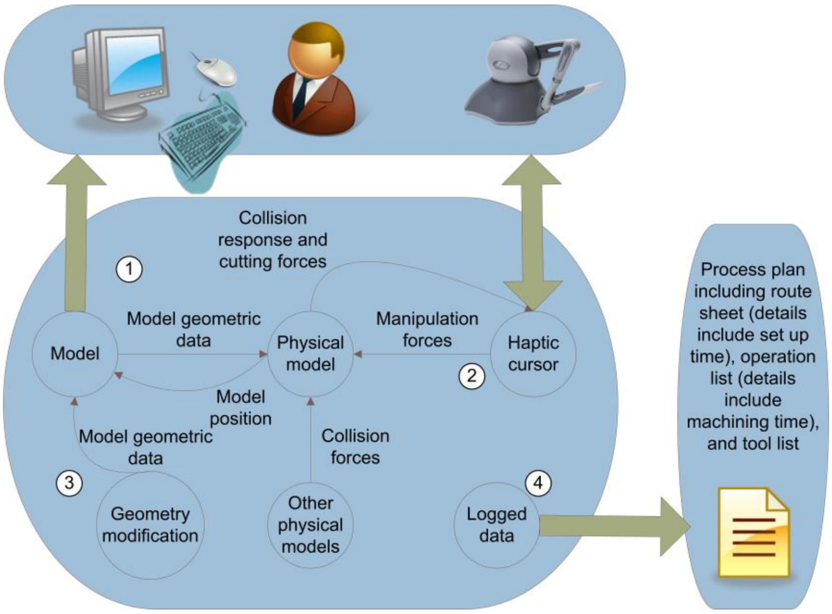


Figure 19 HAPP version 1 system architecture

A fly through approach is taken to navigate the virtual environment. This enables the cursor to be moved quickly through objects until it is in or beside the object to be selected. Once the cursor is in or beside the chosen object it can be selected by pressing and holding a button on the haptic device. When selected the object's local coordinates are displayed.

Once selected, object or tool manipulation is achieved in a semi–realistic manner mixing dynamic and kinematic modes. Objects that are not capable of cutting can be in one of two states: manipulated or static; cutting tools extend these to include a third state: machining (Figure 20).

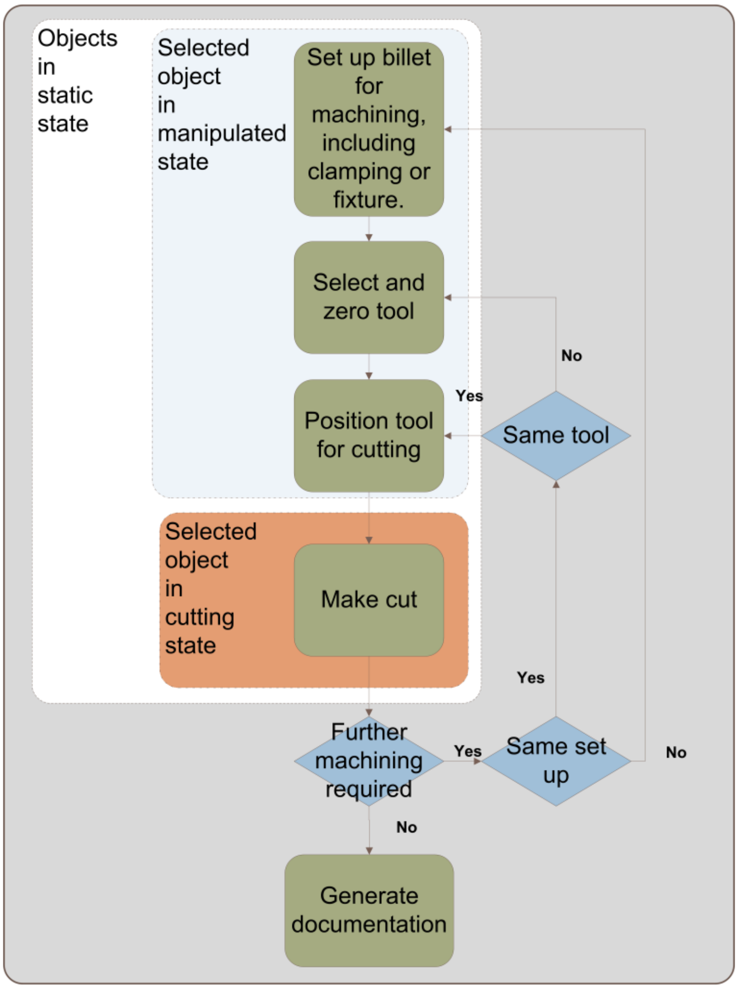


Figure 20 HAPP system operation

These states allow objects to behave naturally whilst being manipulated within the confines and accuracies of the physics engine modelling to remain in a fixed position when not being manipulated or intersecting other shapes as material removal is being carried out.

The static state is entered when the object is not being manipulated. The physical model is in kinematic mode, external forces are ignored and the object remains at the location specified.

The manipulated state is entered when the operator is moving an object or cutting tool and the tool is not in cutting mode. In this state the object's physical model is set to dynamic allowing objects to interact with each other, colliding and responding appropriately; they cannot penetrate each other and external forces such as weight and friction can be applied to the model. In order to manipulate an object with the haptic device whilst in the dynamic state the interaction between the object and the haptic device is modelled by an extended version of a constraint-based "god object algorithm" for generating haptic forces [126]. A spring-like force is created between the object's model and the haptic cursor. As the operator moves the haptic cursor the physical model attempts to follow; however, this is not always possible since the haptic cursor is unconstrained and can move freely through all objects and the manipulated model cannot. This part of the algorithm is supplied as part of the OpenHaptic libraries but is further extended in the application to include other forces acting on the tool avatar such as weight, gravity and collision response. After summing all the contributing forces generated from collisions, physical properties and haptic manipulation, the physics engine will calculate an updated position for the object being manipulated. If, as a result of these forces, the manipulated objects position does not coincide with that of the haptic cursor the difference in position is fed back to the haptic device. In this way, the operator feels inertia or recoil from a collision through the haptic device (Figure 21). Manipulated objects can be locked and datumed in a specific axis by keyboard selection as in the case in real machining; this is achieved in the virtual world by disabling the force update of a particular axis in the physics engine, thus the axial motion of the tool is constrained in a manner similar to that of the tool type selected. This technique is known as a virtual fixture and aids the operator in moving and positioning the tool more accurately.

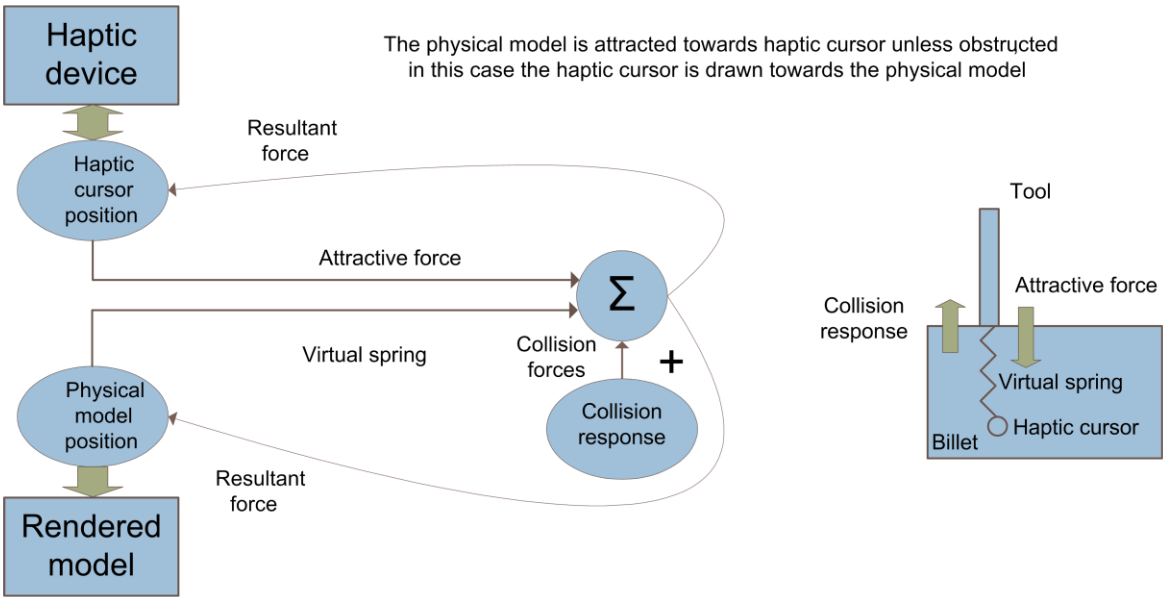


Figure 21 Haptic cursor and model position, control loop

If a tool is selected and turned on then the machining state is entered. The machining state is defined as when a cutting operation is being performed; during this state collision data is ignored, objects are able to penetrate each other and a haptic force is directly rendered to the haptic device. Once enabled, the tool is constrained to its machining axis and vibrates, as in the case of conventional machining processes. In the case of drilling, the tool is constrained in the vertical z-axis while during milling it is constrained to the horizontal x- and y-axes and for turning it is constrained to the longitudinal axis. A routing methodology is implemented for the machining simulation, where the operator moves the tool instead of as in some real world processes, such as the billet table in milling. This was because setting up the tool and then moving the billet is less efficient in terms of manipulations and operations in the VE and as reported in 3.3.1 absolute realism is not necessary for a VR planning environment. As cutting takes place the haptic tool vibrates, the vibration is realised by applying a sinusoidal force directly to the haptic device is representative of the fact that 'cutting' is taking place and is not correlated to any machining parameters, i.e. feed, cutting speed or depth of cut. This makes use of the extra channel of communication opened up by the haptic device to the operator, signalling that the device is on without further loading the visual communication channel.

5.5 System implementation

A virtual machining environment was created (Figure 22) which displays a work surface; selection of tools including: a 5mm drill bit, 10mm drill bit and 16mm end mill; clamps; modular fixture library including locating pegs, clamps, bolts and blocks; and a coordinate measuring machine (CMM) probe.

A planner is able to simulate a machining process, sequence operations, select tools, calculate machining times, determine work holding requirements including set up time calculations and generate planning documentation and costing. Furthermore, by making use of the modular fixture library the planner can also carry out conceptual and detailed fixture design and verification.

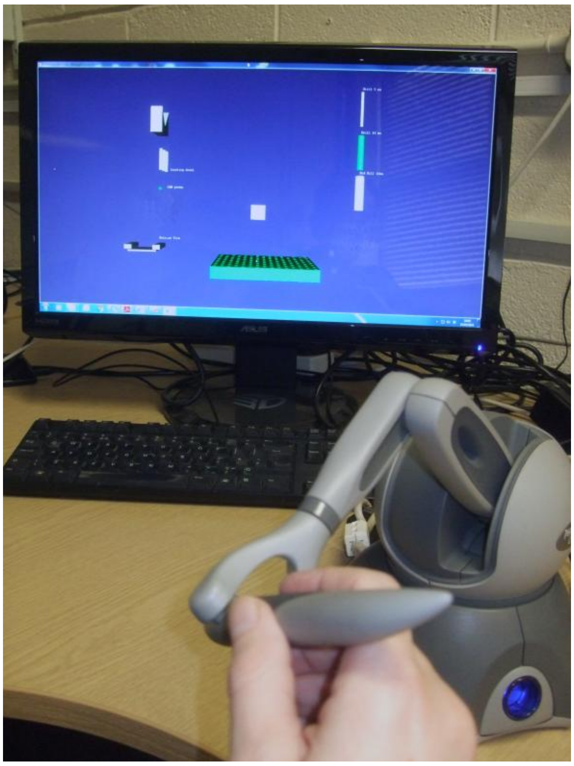
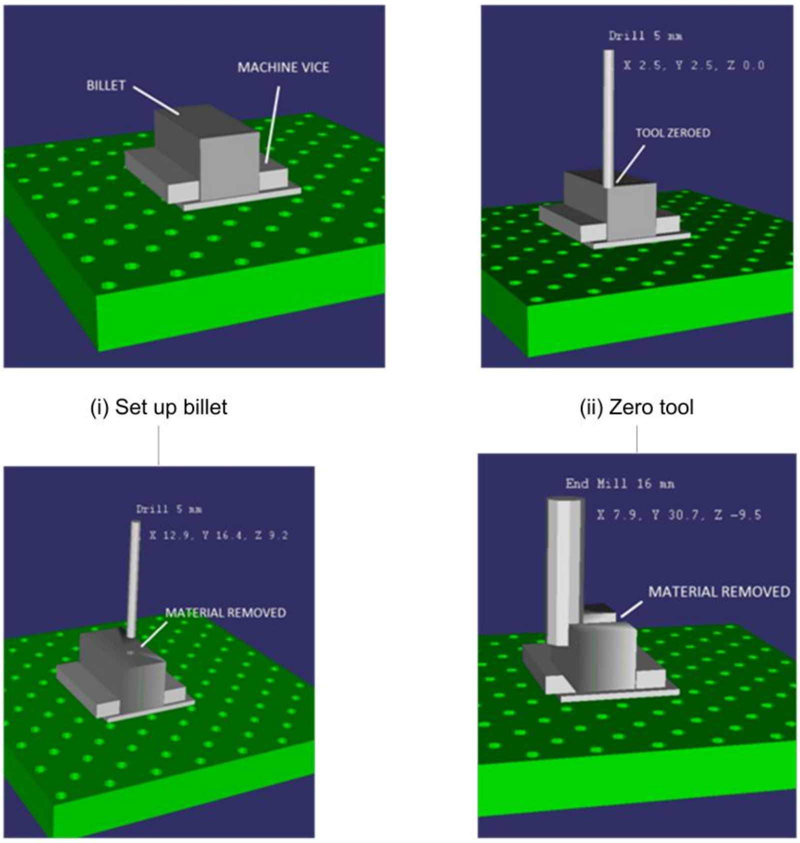


Figure 22 The HAPP system

To begin planning the operator starts by picking up a billet of material and placing it on the work surface. Once the clamps or fixtures have been selected and positioned to hold the billet (Figure 23 (i)), machining can commence. Initially as in real world practices a tool is selected and zeroed against the job (Figure 23(ii)). At this stage tool movement is unconstrained and the operator can move it in a freehand manner, although individual axes can be locked as in a real machining environment to help position the tool if required. Tool coordinates are displayed as an offset from the tool zeroed position. The operator can check for tool clearance between tool and clamp/fixture before activating the tool for cutting. On activation a vibration is fed back through the haptic device to indicate cutting is enabled and the tool becomes constrained along its axis of operation.

For drilling the tool is constrained to its vertical axis and for milling the tool is constrained to the horizontal x-axis. The operator can then virtually 'machine' the billet using the routing machining method and can observe the material being removed in real time (Figure 23(iii)). At the end of each cut, the operator is able to measure the material removed with a virtual CMM probe.



(i) Set up billet

(ii) Zero tool

(iii) Remove material by either drilling or milling

Figure 23 Examples of HAPP operations

Finally after simulating the manufacturing process, a process plan with associated cost sheet can be automatically generated or a fixture plan and an associated time/cost sheet if required.

An example of an automatically generated process plan for a clamp (Figure 24) is given in

Figure 25 which requires a 10mm through hole to be drilled and two 2mm shoulders to be milled.

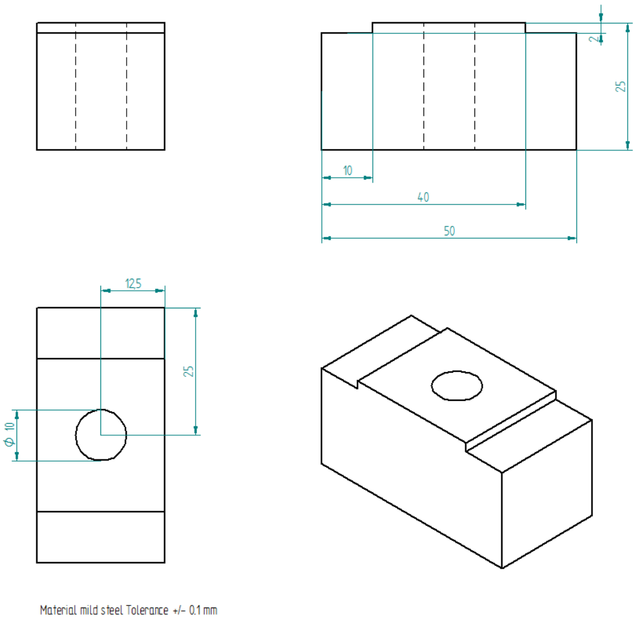


Figure 24 Example clamp

Route sheet				
Operation Number	Machine description	Operation description	Tooling details	
10	Drilling station	Clamp billet	Machine vice	
10		Drill top face -25mm	5mm drill	
10		Drill top face -25mm	10mm drill	
10		Deburr and examine	File	
20	Milling station	Clamp billet	Machine vice	
20		Mill top face -2mm	16mm end mill	
20		Mill top face -2mm	16mm end mill	
20		Deburr and examine	File	
Operation sheet				
Operation Number	Cutting speed (RPM)	Cutting feed (mm per min)	Machining time(seconds)	
10	1909	381	5	
10	954	238	8	
20	298	298	13	
20	298	298	14	
Tool list				
Machine vice				
5mm drill				
10mm drill				
16 mm end mill				
File				
Cost sheet				
Operation	Set up time (seconds)	Machining time (seconds)	Tear down (seconds)	Examine (seconds)
Clamp billet	30			
Set	300			
Drill top face -25mm		4		
Drill top face -25mm		4		
Remove	30			
Deburr and examine				120
Clamp billet	30		300	
Set	300			
Mill top face -2mm		19		
Remove			300	
Deburr and examine				120
Total time (Seconds)	Cost			
1557	£21.63			

Figure 25 Example process plan.

A fixture plan for a non-prismatic part, with a stock already cut to size that only requires a hole to be drilled in the top surface, is shown in Figure 26. The modular fixture library includes a v-block, locating and support pegs and a modular clamp. Associated component lists and assembly/disassembly sequences are shown in Figure 27 and Figure 28.

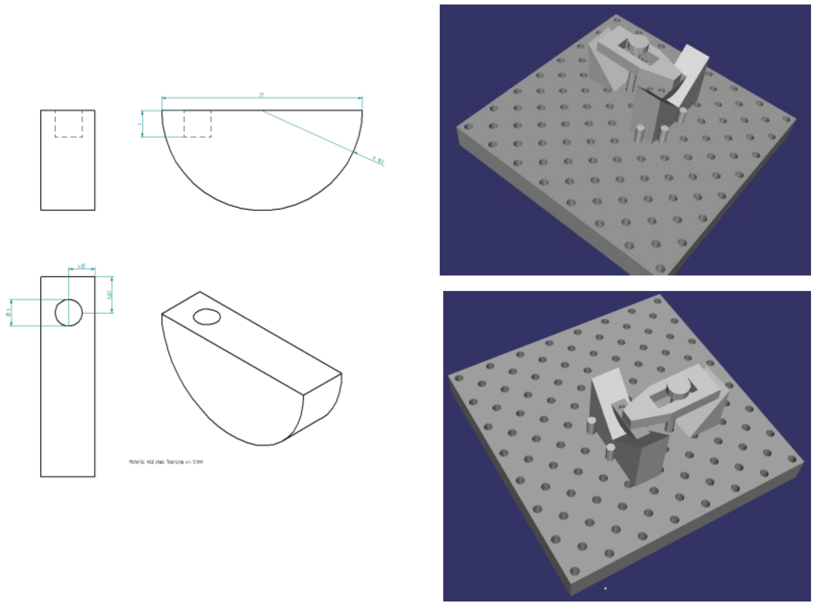


Figure 26 A typical HAPP set up

Operation Number	Description	Setting up (seconds)
10	Locating Dowel A	30
	Locating Dowel B	30
	V block	30
	Clamping billet	30
	Clamp	30
	Clamp heel	30
	Clamp bolt	30
Total Time	seconds	210
Total Cost	£	2.94

Figure 27 Example of a fixture assembly sequence time and cost

Tool List
Locating Dowel A
Locating Dowel B
V block
Clamp
Clamp heel
Clamp bolt

Figure 28 Example of fixture component list

The fixture planning in particular can be seen to build upon previous VA work as reported in 3.4.1, including information such as: operation number, work centre, assembly instruction, tooling and actual assembly time with instructions being stored as a sequence of written instructions and pictures. This clearly demonstrates the application of an existing technology in a new area.

5.6 Pre-pilot study

The aim of the pre-pilot study was to carry out an initial investigation of the interface, determining if the HAPP system was usable for participants to simulate the set up and machining of parts. No evaluation of generated plans was carried out.

5.6.1 Experimental Method

An important factor in usability testing is the test approach; several approaches exist [141]:

- Automatically, where a user interface specification is assessed by software.
- Empirically, where usability is assessed by testing the interface with real users.
- Formally, where model and formulas are used to calculate usability measures.
- Informally, where usability is based on rules of thumb and the general skill and experience of the evaluators.

Although one of the most difficult and costly to implement, empirical testing or “user based testing” is found to be more effective at finding serious defects and the use of rich scenario-based tests developed by end users and sample representatives of end users to be favourable [142]. For this reason user based testing was implemented and a usability evaluation method followed as illustrated in Figure 29.

In this pre-pilot study six participants were asked to carry out a predefined task (5.6.2) and observed while doing so. The results were collected by observation.

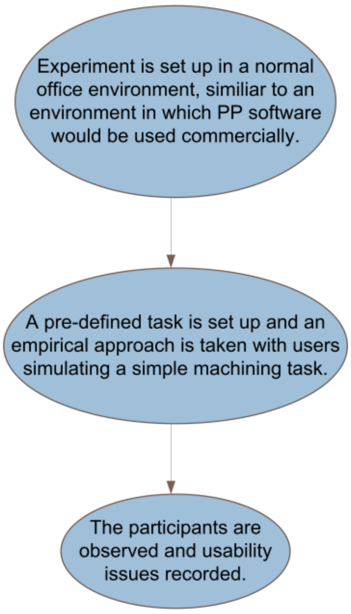


Figure 29 Evaluation method for CAPP

5.6.2 Pre-pilot study task: simulate the machining of a simple milled part with one set up operation

The component in Figure 30 requires a 2mm deep shoulder milled at one end and two 5mm diameter holes drilled side by side to full depth in the centre. The drawing and virtually machined part are shown in Figure 30.

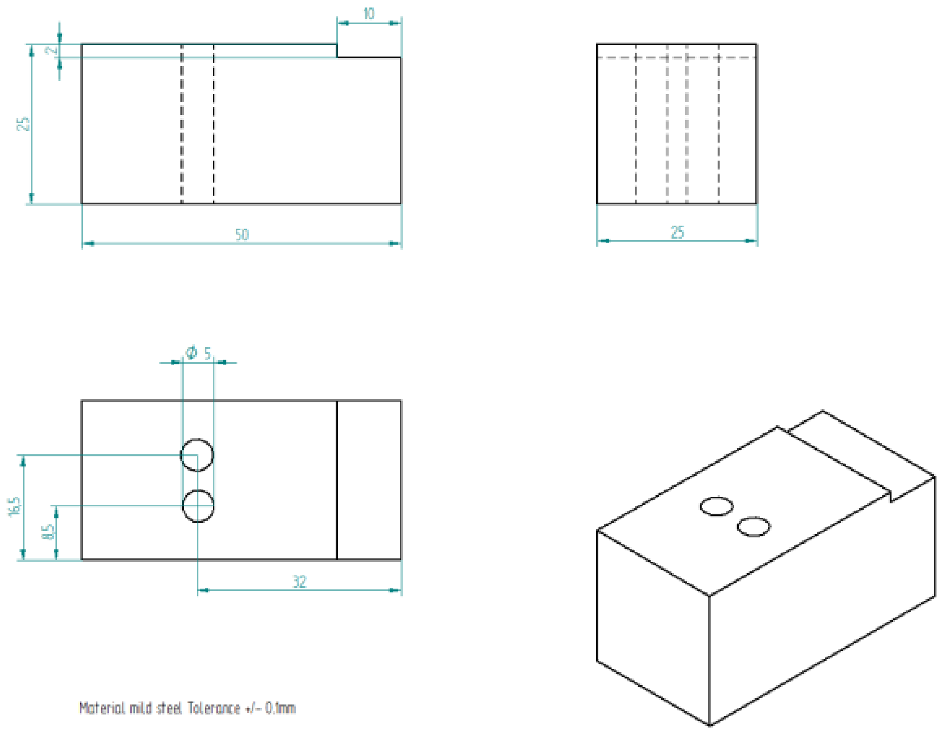


Figure 30 Example 1 – Clamp Part Number HWEPS2589.

5.6.3 Results

Observations made during the experiment are shown in Table 7.

Table 7 Results of pre-pilot evaluation of HAPP

Participant	Observations
1	Difficulty in locating the depth of an object when trying to select it.
2	Difficulty in locating the depth of an object when trying to select it.
3	Difficulty in locating the depth of an object when trying to select it. Had to re-start as operator became completely disorientated and lost the location of the model in the VE.
4	Difficulty in locating the depth of an object when trying to select it.
5	Difficulty in locating the depth of an object when trying to select it.
6	Difficulty in locating the depth of an object when trying to select it. Operator mistakenly switched viewpoint mid task and started working from rear view.

Observing the task revealed two initial significant issues. Firstly allowing the operator to operate the viewpoint through the mouse ultimately ended up in the operator becoming lost in the virtual environment. Secondly, depth perception was a problem; operators struggled to select the correct object.

5.6.4 Discussion of results of pre-pilot evaluation

The evaluation method was sufficient to capture an initial insight into the usability of the system interface, capturing two unforeseen issues, however this evaluation methodology was not sufficient to analyse the usability of the system for process planning, since no plans were assessed in the pre-pilot evaluation and no method of evaluating them was defined. In order to achieve this, a more detailed usability methodology was required. To progress the development of the interface and make it more usable the viewpoint control had to be reduced and some means of aiding the operator with depth perception added.

5.7 Summary

A prototype virtual process planning system called HAPP was developed. This allowed process planners to simulate the machining of components comprising features that require machining on a pillar drill and/or a 2.5D-axis milling machine. This included loading a billet of a predefined size, clamping it in position, carrying out a sequence of cutting operations in real time, tearing down or re-setting in preparation for more machining operations and logging the data required to subsequently generate a process plan and time and cost data.

By meeting these functional requirements of a process planning system Research Objective 1 was met: "To develop a haptic aided process planning system with desired operational features, i.e. job set-up, machining, job tear down, time and cost estimation and automatic plan generation"; however these plans were not validated at this stage.

Finally an initial pre-pilot study was carried out on a small user group evaluating the system interface. It was found to be useable to simulate basic machining tasks but improvements were required in particular viewpoint control and depth perception. To fully evaluate the usability of the system a more thorough usability evaluation methodology was required.

Chapter 6 Pilot study

6.1 Introduction

In Chapter 5, a prototype haptic aided process planning system was developed and a pre-pilot study carried out. At this stage the system was further refined and a more in-depth study of HAPP carried out. A systematic approach enabling the usability evaluation of cross platform process planning systems was developed and applied to both HAPP and traditional manual process planning demonstrating its usefulness in comparing process planning approaches. The usability analysis was undertaken in two parts, initially with objective data and then with subjective data, thus any opinion was reinforced by fact.

6.2 System modifications

The issues identified in the pre-pilot study promoted two changes to the HAPP interface, namely viewpoint navigation and depth perception. To address system navigability the mouse controlled viewpoint was changed to a keyboard-controlled viewpoint with only four different views permitted i.e. front, side and plan elevations. To aid depth perception [48] stereovision was incorporated with the user wearing active shutter glasses. The updated system specification is illustrated in Table 8.

Table 8 HAPP version 2 updated specification

	HAPP	Description of how HAPP meets specification.
Process planning essential requirements		
Drawing interpretation and material evaluation.	x	A model of the raw material will be rendered on the monitor in **3D** and the operator can manipulate the viewpoint **through 4 set viewpoints by keyboard macros**.
Process selection and sequencing.	x	The operator will be able to select either a centre drill or 2.5D milling machine in any order they choose.
Machine selection and operations sequencing.	x	The operator will be able to manipulate the billet and cutting tools to carry out cutting sequences in any order they choose with the haptic device
Tooling selection.	x	A 5mm drill, 10mm drill and a 16mm slot mill will be included. Tool access can be verified before cutting sequence is started.
Setting the process parameters.	x	Process parameters will be automatically included from set values in the Machinery handbook.
Calculate machining times	x	Times will be calculated from standard equations.
Determining the work holding requirements.	x	A machine vice and clamp set will be included to enable the operator to plan the set up before machining. These will be manipulated through the haptic device.
Calculate set up time	x	The set up time will be calculated for the set up simulation.
Selecting quality assurance methods.	x	A virtual CMM probe will be included to measure material removed.
Documenting the process plan.	x	Process plans as described in [3] [5] will be generated automatically after the planner has finished simulating the machining sequence.
Costing the plan.	x	A cost is automatically generated with the process plan based on an hourly rate multiplied by the set up and machining times.
Process planning desirable characteristics specific to user		
Involve user in some part of the decision making process	x	All processes are carried out by an operator and specialist knowledge will be unobtrusively logged.
Include a user friendly interface	x	A haptic VR interface will be implemented.

The illustration of the system architecture is also updated in Figure 31.

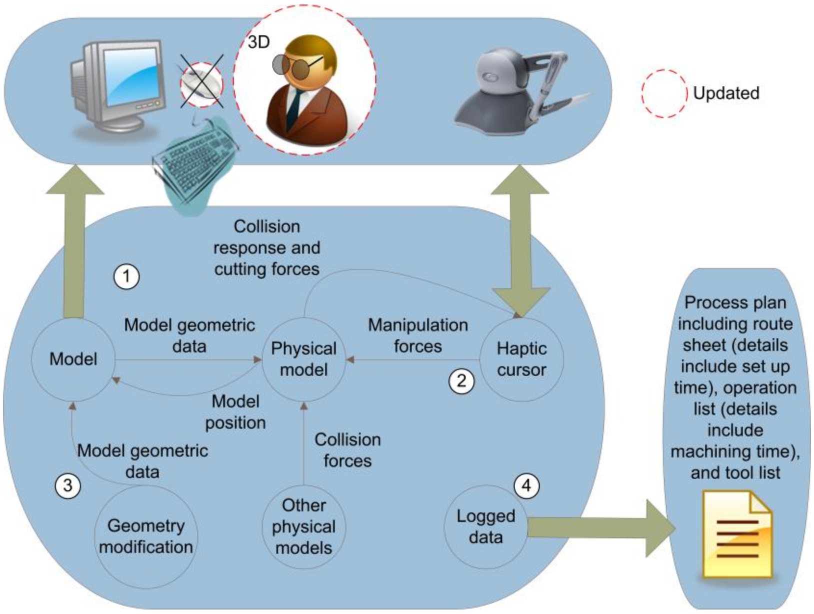


Figure 31 HAPP version 2 system architecture

6.3 Evaluation method modifications

A more formalised evaluation method was developed for the pilot study in line with the key points identified in Table 5.

The evaluation method was updated to include a clear definition of the system context since it is important that the context is as close as possible to that used for process planning in industry where a variety of process planners will use the system in an office environment. Therefore, the users selected were individuals with levels of experience in process planning ranging from novice to expert. An office environment usually consists of a desk and PC, there may be other people in the room but the environment will generally be quiet and the tasks given were to generate process plans for objects that can be machined within the constraints of the tools and processes provided.

Further, the evaluation method was refined to capture data regarding user satisfaction, learnability effectiveness and efficiency:

Satisfaction: A SUS [143] questionnaire was added to the evaluation method to collect data regarding satisfaction, it was chosen because: it is suitable for any interface [97], known to be robust [97], yields reliable results across different sample sizes [98] and includes a measure of perceived learnability [99]. The SUS questionnaire consists of 10 statements that relate to the system being reviewed. The participant is required to rate their strength of feeling through a five point Likert scale varying from 'Strongly agree' to 'Strongly disagree' with regard to the system. The SUS statements are as follows:

1. I think that I would like to use this system frequently.
2. I found the system unnecessarily complex.
3. I thought the system was easy to use.
4. I think that I would need the support of a technical person to be able to use this system.
5. I found the various functions in this system were well integrated.
6. I thought there was too much inconsistency in this system.
7. I would imagine that most people would learn to use this system very quickly.
8. I found the system very cumbersome to use.
9. I felt very confident using the system.
10. I needed to learn a lot of things before I could get going with this system.

The SUS score is calculated by adding the score for positively worded and negatively worded questions and multiplying by 2.5, to normalise the value between 0 - 100. Positively worded items (1, 3, 5, 7 and 9) equal the scale position (strongly agree = 5, strongly disagree = 1) minus 1 and negatively worded items (2, 4, 6, 8 and 10), equal 5 minus the scale position. The score is a useful quantification of the perceived usability measure but to further aid a researcher in evaluating a system, an adjective scale rating was added by Bangor [144]. In this scale rating a description was given to provide more meaning to the SUS score (Figure 32).

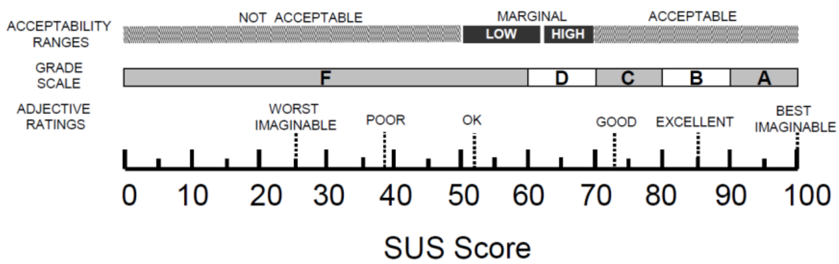


Figure 32 Adjective scale rating for SUS score, Bangor [144]

System learnability scores were derived for each user group from question 4 and question 10 [99]. The total equals the addition of both values, which is then multiplied by 12.5 to normalise the score to a value between 0-100. The individual question values were calculated as for negatively worded questions.

This questionnaire was complimented with a further three statements:

11. I was completely immersed in the task?

12. My mental workload was reduced?
13. I wasn't stressed at all?

Mental work load was added as a subjective measure of mental effort [96]. This helped identify if users felt virtual environment made the planning task easier. Users were also asked if they felt stressed in order to understand how at ease the operator felt within each environment. If participants were unsure of the meaning of the question they were permitted to ask for clarification.

These questions were answered in the same way as the rest of the questionnaire with a five point Likert scale, ranging from "strongly agree" to "strongly disagree" but were not included in the calculation of the SUS score. The question regarding immersion was included as it is often referred to in computer game circles as critical to game enjoyment and is an indicator of the level of attention applied [145].

Since the questionnaires only reveal the levels of satisfaction and learnability felt by the user, a SWOT analysis, Strengths, Weaknesses, Opportunities and Threats (SWOT) [146] was also added to the evaluation method further enhancing the observational data captured during a system study, participants were asked to fill out this analysis to reveal the underlying contributing factors as to the level of usability attained by the system.

Objective measures were also added to the evaluation method in order to capture the effectiveness and efficiency of the system.

Effectiveness: Objective measures, found in a review by [96] used to measure effectiveness include expert assessment, binary task completion, accuracy, recall, completeness and quality of outcome. Expert assessment is the grading of the outcome of the system by an expert, binary task completion refers to the task being successfully completed or not, accuracy relates to the number of errors operators make whilst carrying out the task, recall measures how much information can be remembered by the operator after using the system, completeness relates to how well tasks are solved and quality of outcome aims to measure the quality of the work product. In this research the effectiveness was measured by an expert assessment of the quality of the outcome.

A set of quality measures for process plans were derived from [147], where Information Quality (IQ) is described as "information which conforms to a set of specifications or meets or exceeds consumer expectations.”. Forty five professionals were asked to assign specific information quality dimensions with regard to information quality. The dimensions listed included free-of-error, concise representation, completeness, consistent representation, appropriate amount, relevancy and understandability. In order to evaluate the effectiveness of the generated plan these are interpreted as conciseness, clarity, consistency, completeness and errors where:

- conciseness relates to concise representation and appropriate amount;
- clarity to the measure of understandability, this work analyses understandability with respect to clear legible written instructions;
- consistency refers to consistent representation of specific information;
- completeness considers the completeness of the plan with regard to sufficient information to manufacture the product correctly;
- errors relates to free-of-error and documents the errors in the plan .

Efficiency: In [96] measures of efficiency being used were found to include input rate, usage patterns, communication effort, learning measures, mental effort and task completion time. Input rate measures the speed at which a user can input data, usage patterns measures how an operator uses the interface and this can include key presses or measures of deviation from an optimal solution, communication effort is related to group work and measures resources necessary to communicate and learning measures use changes in efficiency as an indicator of learning and mental effort measures the amount of mental effort required by the user during interaction. Task completion time is a measure of how long it takes to complete the predefined task and is one of the most common means of measuring a system’s efficiency [96]. However, this can be further defined in terms of its cognitive component (CC) and physical-motor component (MC) . This is achieved by applying the GOMS-KLM model [100] to the task being assessed. The Goals, Operators, Methods and Selection rules (GOMS) framework provides a method to analyse a user’s interaction with a computer in its elementary actions with the Key-stroke Level Model (KLM) a particular implementation of this framework. According to this model, tasks can be described in terms of acquisition and execution time. “During acquisition the user builds a mental representation of the task and during execution the user calls on system facilities to accomplish the task.” [100]

$$T_{task} = T_{acquire} + T_{execute} \tag{1}$$

Where:

T_{task} = The total time to complete the task.

$T_{acquire}$ = The time taken to build a mental understanding of the task.

$T_{execute}$ = The time taken using the system facilities' to accomplish the task.

The execution part of a task consists of a physical-motor operator T_{PMO}, a mental operator T_M and a system response operator T_R.

$$T_{execute} = T_{PMO} + T_M + T_R \tag{2}$$

Where:

T_{PMO} = The time taken by the physical-motor actions.

T_M = The time taken for mental (cognitive) processes.

T_R = The time taken for the system to respond to the operator's input.

A physical-motor operator (T_{PMO}) consists of actions such as pressing a key or moving the mouse, whilst a mental operator (T_M) is the operator deciding which command to call; the system response operator (T_R) is the time that is required for the system to respond to the operator’s input. In this case this model is simplified and does not include the system response operator given the environment operates at interactive rates and this time period is considered trivial i.e. T_R -> 0. Therefore:

$$T_{execute} = T_{PMO} + T_M \tag{3}$$

The Task Completion Time (TCT) description can now be grouped in terms of mental components and physical motor components.

$$TCT = T_{acquire} + T_M + T_{PMO} \tag{4}$$

Where:

$T_{acquire} + T_M$ = Mental components.

T_{PMO} = Physical components.

When functionally decomposed the task of process planning falls broadly into two phases: (1) strategising, where the planner is thinking about how best to machine and communicate the plan; and (2) the recording component of that information. This decomposition has been drawn from work by Hamade et al [148] when analysing the learning of CAD systems. It is stated that operating the CAD system requires declarative skills which are analogous to the GOMS-KLM physical-motor component, which include the process of pressing a button and procedural knowledge which is analogous to the GOMS-KLM cognitive component including planning or strategizing. Therefore, when analysing a process planning system in terms of efficiency both the cognitive efficiency and physical motor efficiency must be measured.

The physical motor efficiency was measured as the time spent carrying out haptic manipulation in HAPP: whereas in the traditional environment, the physical motor efficiency was the time spent to copy the final process plan, (writing at an average speed of 117 words per minute [149]). The TCT was measured manually for both process planning tasks and also logged in the HAPP application for the HAPP generated process plan.

6.4 Apparatus

The apparatus used in the experiment consisted of the HAPP software application as outlined in Chapter 5 with the recent modifications implemented as highlighted in section 6.2 and a traditional process planning environment.

The traditional planning environment was implemented using three paper templates drawn from [3], comprising of a route sheet, tool list and operation list (Figure 33). The route sheet documents the route a product will take through the machine shop including: the machine to be used at each stage and a description of the operation to be carried out; the tool list contains all necessary information for the selected tool for each operation and finally, the operation list containing the feeds and speeds for each operation along with the machining time. Each sheet is cross-referenced by an operation number. Also supplied was a 2D drawing of the part. This would accompany the part to be manufactured with the route sheet through the manufacturing process and can be used by the planner to define the plan.

ENGINEERING APPLICATIONS – Route Sheet			
Operation Number	**Machine Description**	**Operation Description**	**Tooling Details/ CNC Reference**
Part Number			**Page of**

ENGINEERING APPLICATIONS – Operation List			
Operation Number	**Cutting Speed**	**Cutting Feed**	**Machining Time**
Part Number			**Page of**

ENGINEERING APPLICATIONS – Tool List				
Operation Number	**Tool No.**	**Tool Offset**	**Tool Description**	**Tooling Material**
Part Number				**Page of**

Figure 33 Abbreviated process plan templates.

6.5 Experimental method

The method for evaluating the usability of both process planning systems is illustrated in Figure 34.

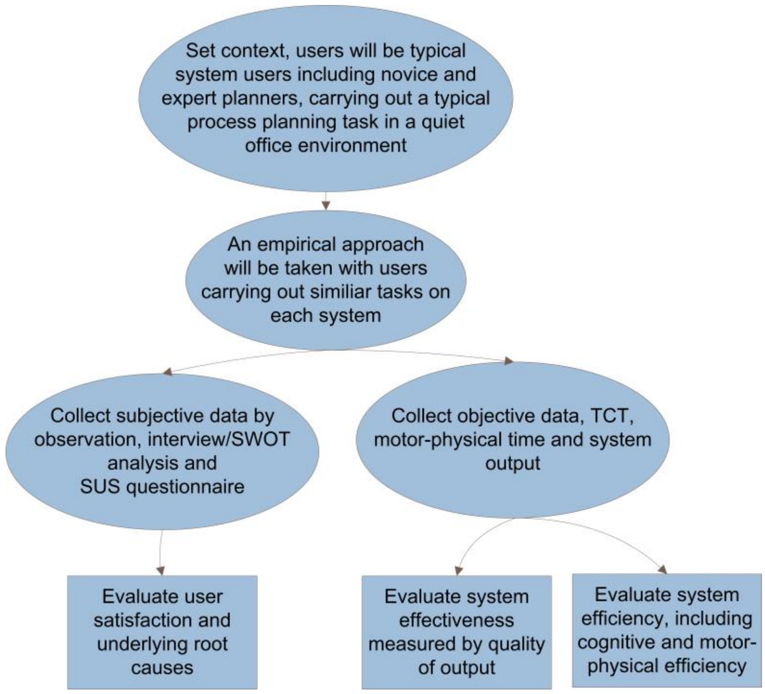


Figure 34 Updated 'Usability' evaluation method for CAPP

Two similar process planning tasks were identified for each environment, the sample parts to be manufactured being different in appearance but requiring the same combination of machining operations. Participants were informed that the billet was cut to the correct external dimensions and they were required to define the operations required to realise the final product. These included: job set up, drill a 5mm diameter pilot hole, drill a 10mm diameter hole, make two cuts with a 16mm diameter end mill and finally tear down the fixtured part and tool set up. The selected user group carried out each task with the initial task being alternated between participants to negate any bias caused by pre-learning.

6.5.1.1 Task 1 - traditionally generated process plan

In order to generate a process plan in a traditional process planning environment each participant was provided with a list of equipment available in the workshop (including photographs) and a set of process plan templates. The machine processes available comprised a pillar drill, 2.5 axis milling machine, vice clamp, work bench and a tool set including a 10mm twist drill, 5mm twist drill and a 16mm end mill (Figure 35).

Figure 35 Machinery and tool suite

The plan templates (Figure 33) were used and little explanation was given on how to complete them other than they should be filled out as completely as possible so that they could be passed to a shop floor operator. If there were areas that required details the planner did not know about then they should leave them blank. Each participant was given a 2D drawing of Figure 36 and, after being given the opportunity to ask any questions was asked to complete the process plan.

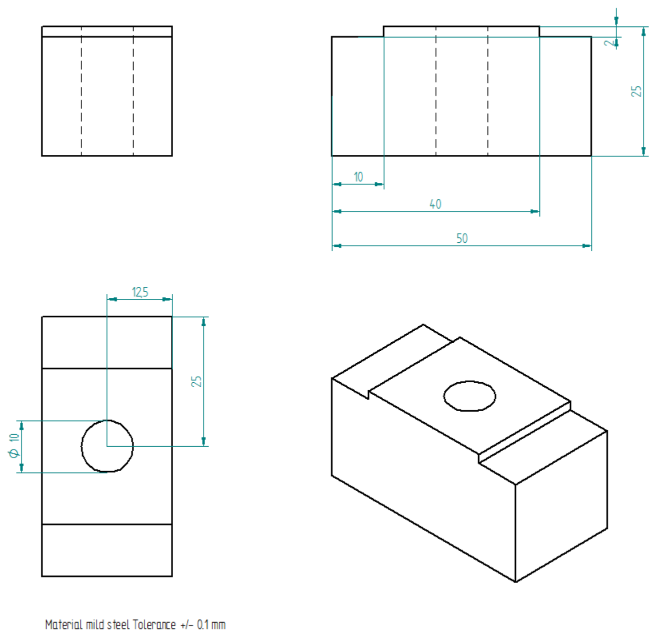


Figure 36 Clamp 1 drawing and benchmark process plan

6.5.1.2 Task 2 – HAPP generated process plan

Using HAPP the participant was asked to simulate the machining of clamp 2 (Figure 37) in order to automatically generate a process plan.

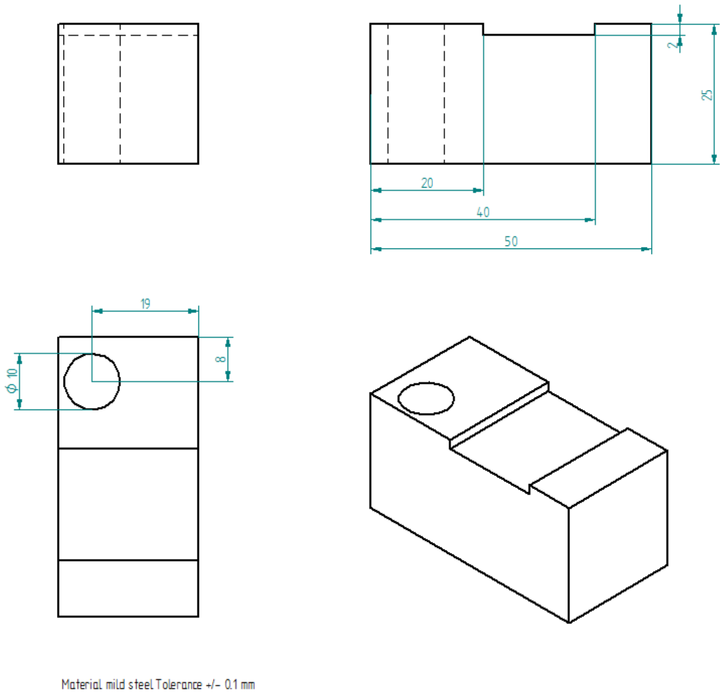


Figure 37 Clamp 2 drawing

A series of warm up tasks were carried out to ensure the user was comfortable with the haptic environment. The initial warm up task required the participant to zero the tool and drill a 5mm and 10mm hole in a billet and then mill a slot; up to this point questions were permitted. For the second warm up task the participants were required to simulate the machining of a similar clamp in the virtual environment and automatically generate a process plan. During the final warm up task the participant was asked to copy a demonstration of the machining of a similar clamp. After the warm up exercises were completed the participant was given the drawing for Clamp 2 and asked to use HAPP to simulate the machining of the clamp in order to automatically generate the process plan.

6.6 Results and analysis

The results and their analysis are separated into objective data and subjective data. The objective data shows the effectiveness and efficiency of the system. The subjective data captures the perceived satisfaction of the users and their perception of the systems' learnability. Finally a discussion of the effectiveness of the evaluation method is conducted.

6.7 Objective results

The results were analysed in two stages; the first regarding the quality of the plan output as a measure of system effectiveness and the second with regard to the task completion time and associated derived mental and physical effort. Output plans generated from Task 1 are shown in Figure 38 and Task 2 in Figure 39.

ENGINEERING APPLICATIONS – Route Sheet

Operation Number	Machine Description	Operation Description	Tooling Details /CNC Reference
1	milling	milling off the edges (left)	16 mm mill
2	milling	Milling right edge	16 mm mill
~~3~~	~~Mill work~~	~~pillar drill~~	
3	work bench		
4	work bench	centre punch drilling location	centre punch
5	drill	predrill 5 mm	5mm drill
6	drill	drill 10mm	10mm drill

ENGINEERING APPLICATIONS – Operation List

Operation Number	Cutting Speed	Cutting Feed	Machining Time
1	1600 rpm	2 mm s^{-1}	22.5 seconds
2	1600 rpm	2 mm s^{-1}	22.5 seconds
4	centre punch		10 seconds
5	20 rps	1 mm s^{-1}	27 seconds
6	20 rps	1 mm s^{-1}	27 seconds

ENGINEERING APPLICATIONS – Tool List

Operation Number	Tool No.	Tool Offset	Tool Description	Tool Material
1	M16 end	2mm	16mm End mill	? ?
2	M16 end	2mm	16mm End mill	
4	centre punch		centre punch	
5	5mm drill	2mm	5mm drill	
6	10mm drill	2mm	10mm drill	

Figure 38 A process plan generated for Task 1 via traditional process planning

Route sheet			
Operation Number	Machine description	Operation description	Tooling details
10	Drilling station	Clamp billet	Machine vice
10		Drill top face -26mm	5mm drill
10		Drill top face -26mm	10mm drill
10		Deburr and examine	File
20	Milling station	Clamp billet	Machine vice
20		Mill top face -2mm	16mm end mill
20		Mill top face -2mm	16mm end mill
20		Deburr and examine	File
Operation sheet			
Operation Number	Cutting speed (RPM)	Cutting feed (mm per min)	Machining time(seconds)
10	1909	381	5
10	954	238	8
20	298	298	13
20	298	298	14
Tool list			
Machine vice			
5mm drill			
10mm drill			
16 mm end mill			
File			

Figure 39 A process plan for Task 2 generated automatically via HAPP

6.7.1 Results for the measurement of effectiveness

The effectiveness is measured by a direct comparison to the benchmark process plans (Figure 40 and Figure 41). Measures as described in 6.3 were applied including conciseness, clarity, consistency, completeness and errors (Table 9).

Table 9 Information quality measures to evaluate plan effectiveness

Measures of quality for system output	Conciseness	Clarity	Consistency	Completeness	Errors
Description	Number of words in route sheet, operation description	The legibility of the document	The uniformity of information across plans	Comprehensiveness of information	Inaccuracies likely to cause incorrect manufacture
Weighting	1/5	1/5	1/5	1/5	1/5

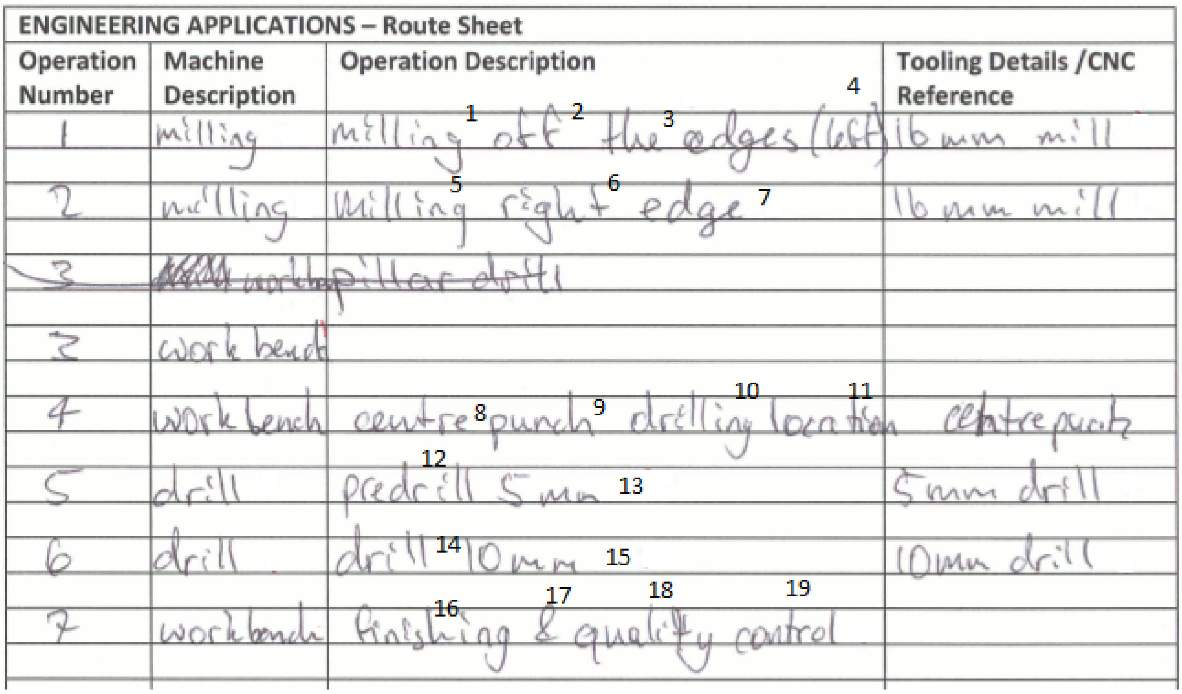
Route sheet			
Operation Number	Machine Description	Operation Description	Tooling details
10		Locate billet in machine vice	Machine vice
	Vertical mill	Mill steps Width 10mm Depth 2mm	16mm diameter end mill, 4 flute
20	Fitting bench	Debug and examine	File
30		Locate billet in machine vice	Machine vice
30a	Pillar drilling machine	Centre drill hole position	5mm diameter twist drill
30b		Drill through hole Hole diameter 10mm	10mm diameter twist drill
40	Fitting bench	Deburr and examine	File
Operation sheet			
Operation number	Cutting Speed	Cutting Feed	Machining Time
10	298 RPM	298mm/minute	10 seconds
30a	1909 RPM	381mm/minute	5 seconds
30b	954 RPM	238 mm/minute	8 seconds
Tool list			
	Machine vice		
	End mill 16mm, 4 flute		
	File		
	5mm diameter twist drill		
	10mm diameter twist drill		

Figure 40 Benchmark PP clamp 1

Route sheet			
Operation Number	Machine Description	Operation Description	Tooling details
10		Locate billet in machine vice	Machine vice
	Vertical mill	Mill slot Width 20mm Depth 2mm	16mm diameter end mill, 4 flute
20	Fitting bench	Debug and examine	File
30		Locate billet in machine vice	Machine vice
30a	Pillar drilling machine	Centre drill hole position	5mm diameter twist drill
30b		Drill through hole Hole diameter 10mm	10mm diameter twist drill
40	Fitting bench	Deburr and examine	File
Operation sheet			
Operation number	Cutting Speed	Cutting Feed	Machining Time
10	298 RPM	298mm/minute	10 seconds
30a	1909 RPM	381mm/minute	5 seconds
30b	954 RPM	238 mm/minute	8 seconds
Tool list			
	Machine vice		
	End mill 16mm, 4 flute		
	File		
	5mm diameter twist drill		
	10mm diameter twist drill		

Figure 41 Benchmark PP clamp 2

Conciseness: the number of words were counted on the route sheet operation description for the benchmark plan, HAPP generated plan and the manually created plan. Figure 42 demonstrates a plan with a word count of 19 in the operation description column, which was used as a measure of conciseness.



ENGINEERING APPLICATIONS – Route Sheet			
Operation Number	Machine Description	Operation Description	Tooling Details /CNC Reference
1	milling	milling 1 off 2 the 3 edges (left) 4	16 mm mill
2	milling	Milling 5 right 6 edge 7	16 mm mill
~~3~~	~~work pillar drill~~		
3	work bench		
4	work bench	centre 8 punch 9 drilling 10 location 11	centre punch
5	drill	predrill 12 5mm 13	5mm drill
6	drill	drill 14 10mm 15	10mm drill
7	workbench	finishing 16 & 17 quality 18 control 19	

Figure 42 Example of conciseness measure

The results of the analysis of the Process Plans with regard to conciseness are shown in Figure 43.

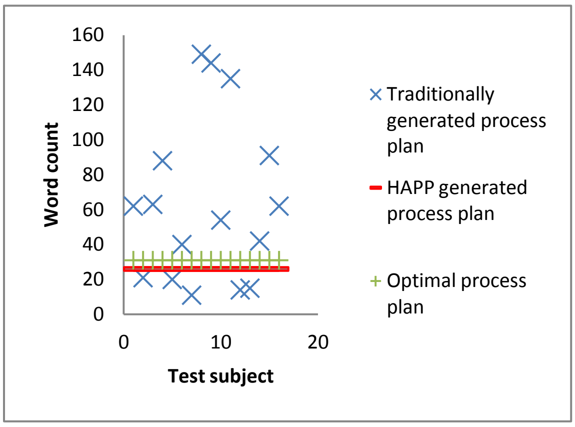


Figure 43 Process plan, measure of conciseness

It can be seen that the conciseness of traditionally generated process plans varies considerably, from too short to overly verbose. The automatically generated plans are far more consistent, although still not perfect; this is due to the difficulty in automating some of the naturally rich features of a descriptive language describing the type of feature to be machined. The resulting description is a little too concise. For example “Mill top face depth - 2mm” as opposed to “Mill steps depth 2mm width 10mm”.

Clarity: marks were awarded from 1 – 3 for grammar, legibility, layout, spelling, punctuation and descriptiveness of the route sheet (Table 10). A report of perfect clarity would score 18 (or 100%). An example of an evaluated plan is given in Figure 44.

Table 10 Marking guide for PP measures of clarity

Clarity measure	Score	Marking guide
Grammar	1	If more than one sentence was poorly constructed.
	2	If only one sentence was poorly constructed.
	3	If all sentences were correctly constructed.
Legibility	1	If more than two words are illegible.
	2	If one word is illegible.
	3	If all items are legible.
Layout	1	If more than one item is not written with boundaries.
	2	If one item is not written within boundaries.
	3	All items are written within boundaries.
Spelling	1	More than one spelling mistake.
	2	One spelling mistake.
	3	No spelling mistakes.
Punctuation	1	More than one punctuation error.
	2	One punctuation error.
	3	No punctuation errors.
Descriptiveness	1	No description of machinable features.
	2	Description of one or more machinable features.
	3	Description of all three machinable features.
Total	18	

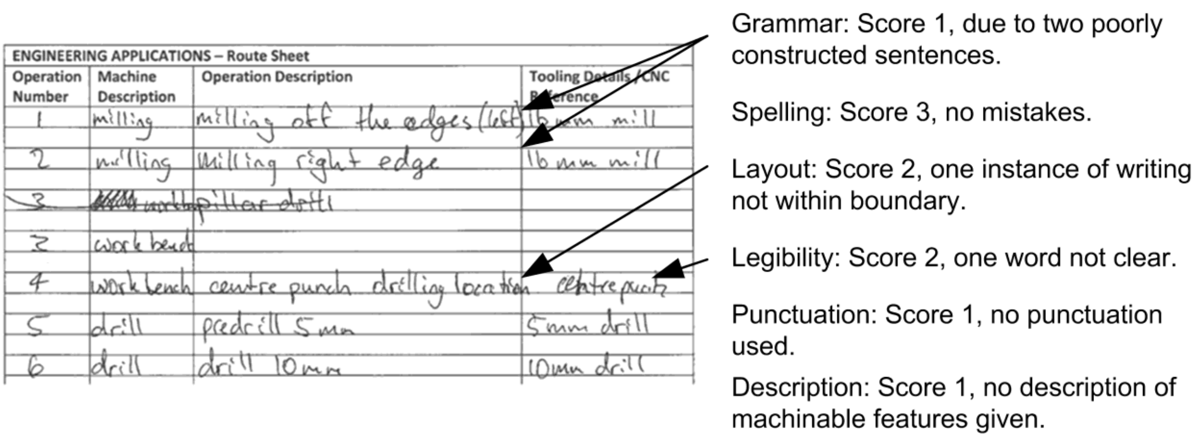


Figure 44 Example of process plan marked for clarity

The results of the process plan with regard to clarity are illustrated in Figure 45.

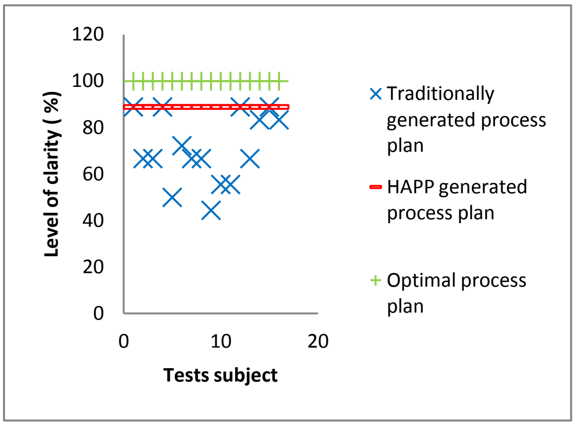


Figure 45 Process plan, measure of clarity

The automatically generated process plans have more clarity than those developed in a traditional manner (Figure 45) but this is as expected since any hand written notes are subject to spelling mistakes, poor hand writing and a failure to write data within allocated boxes. However the virtually generated plans also do not receive full marks since the level of descriptiveness was not quite as high and needs to be embellished. However, the concept of automatically generating understandable, explanatory instructions for process plans was proved.

Consistency: Milling feed rate is illustrated to demonstrate consistency of instruction output. The sample size is smaller as not all participants recorded this level of detail.

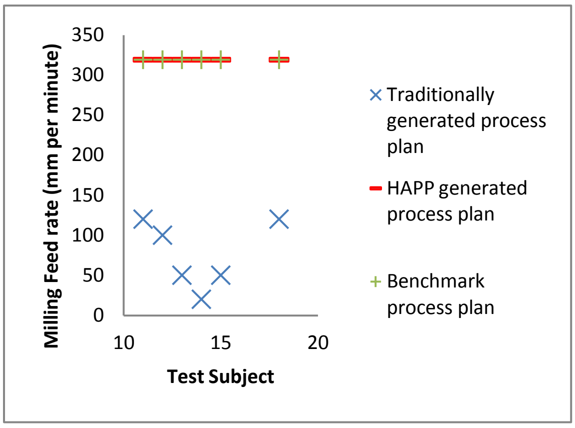


Figure 46 Process plan, example of consistency of output using feed rate

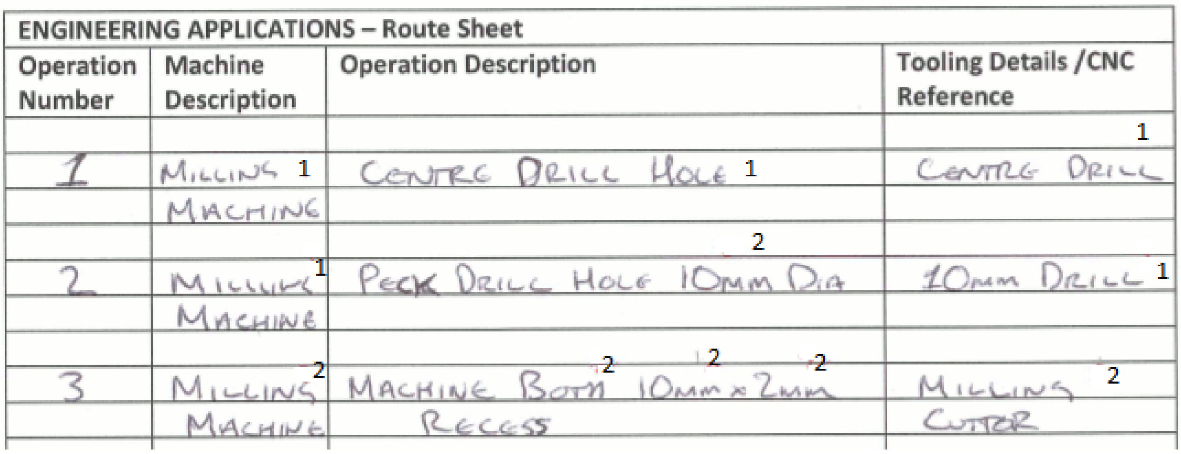
Consistency (Figure 46) was measured by comparing the milling feed rates in plans where they were documented; it was mainly the experts who entered data and it can be seen, even from this perspective, that there is no consistent solution. In reality all answers will allow the part to be machined correctly but this is not consistent with a quality system where processes need to be repeatable. It should also be noted that HAPP generates a much higher feed rate (calculated from tool data literature) due to the local experts placing a higher importance on tool life as opposed to production throughput. This will change depending on shop priorities. A philosophical thought at this point is perhaps the metric used, the Machinery Handbook, is not always correct for all situations. HAPP could also be used to collect local knowledge with regard to feeds and speeds as well as other planning data.

Completeness: Marks were awarded based on the detail of information included in the plan. A guide is given in Figure 47 with a perfect score equal to 44.

Route sheet			
Operation Number	Machine Description	Operation Description	Tooling details
10	(Location implied or stated 1 mark)	Locate billet in machine vice (1 mark)	Machine vice *(1 mark)*
	Vertical mill *(2 marks)*	Mill slot *(2 marks)* Width 20mm *(2 marks)* Depth 2mm *(2 marks)*	16mm diameter end mill, 4 flute *(2 marks)*
20	Fitting bench *(1 mark)*	Debug and examine (1 mark)	File (1 mark)
30	(Location implied or stated 1 mark)	Locate in machine vice (1 mark)	Machine vice *(1 mark)*
30a	Pillar drilling machine (1 mark)	Centre drill hole position (1 mark)	5mm diameter twist drill (1 mark)
30b	(Location implied or stated 1 mark)	Drill through hole Hole diameter 10mm *(2 marks)*	10mm diameter twist drill (1 mark)
40	Fitting bench *(1 mark)*	Deburr and examine (1 mark)	File (1 mark)
Operation sheet			
Operation number	Cutting Speed	Cutting Feed	Machining Time
10	298 RPM (2 marks)	298mm/minute *(2 marks)*	10 seconds *(2 marks)*
30a	1909 RPM *(1 mark)*	381mm/minute *(1 mark)*	5 seconds *(1 mark)*
30b	954 RPM *(1 mark)*	238 mm/minute *(1 mark)*	8 seconds *(1 mark)*
Tool list			
	Machine vice *(1 mark)*		
	End mill 16mm, 4 flute (1 mark)		
	File (1 mark)		
	5mm diameter twist drill (1 mark)		
	10mm diameter twist drill (1 mark)		

Figure 47 Marking guide for process plan measure of completeness

An example of a route sheet marked for completeness is shown in Figure 48.



ENGINEERING APPLICATIONS – Route Sheet			
Operation Number	Machine Description	Operation Description	Tooling Details /CNC Reference
1	Milling Machine 1	Centre Drill Hole 1	Centre Drill 1
2	Milling Machine 1	Peck Drill Hole 10mm Dia 2	10mm Drill 1
3	Milling Machine 2	Machine Both 2 10mm x 2mm 2 Recess 2	Milling Cutter 2

Figure 48 Example of a Route sheet marked for completeness

The results for all plans with regard to completeness are illustrated in Figure 49.

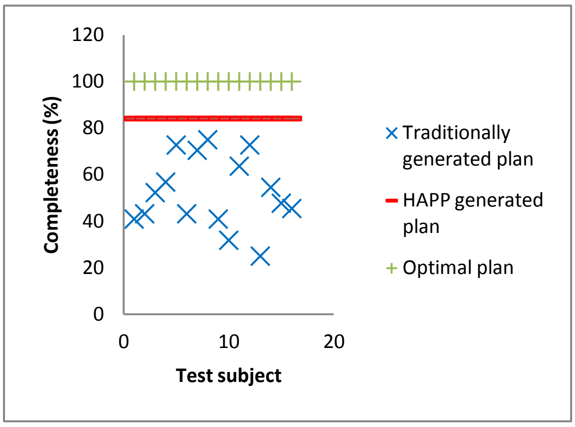


Figure 49 Process plan, completeness

There was a high level of variability in the completeness of the traditionally generated process plans (Figure 49), which was to some extent related to the experience of the process planner. In many cases feeds, speeds and machining times data were left blank, since some participants did not know this level of detail. The completeness of the virtually generated plan was higher on average than the traditionally generated plans by approximately 30%. One of the key reasons for this is HAPP's ability to generated machining times for all operations due to an embedded machining knowledge database. However the HAPP generated plan was marked down when compared to the optimal, since the description of the operation in the operation sheet did not contain as clear a description of the milling cut.

Plan errors: Machined features in the plan were logged accurately within a tolerance of +/- 0.1mm. However, the tasks were not sufficient to expose all mistakes made by the operator whilst simulating the machining of a part. For example the plan indicates a hole of depth

26mm should be drilled but does not indicate the location. It was observed during the experiment that some operators drilled the hole in the wrong location (it was observed that they became so immersed in machining the part they forgot to double check dimensions).

Here it can be seen that the logged data is inaccurate, L_Position(z) should be 8.000 not 9.905. This would drill the hole almost 2mm out of position in the z plane. The haptic logging assumes z to be front to back.

	A	B	C	D	E	F	G	H	I
1	Time(s)	Tool	Tool State	L_Force(x)	L_Force(y)	L_Force(z)	L_Position(x)	L_Position(y)	L_Position(z)
36282	15563916	10mm drill	ON	-0.1125	-0.06466	-0.1031	1.126	-1.391	9.717
36283	15577133	10mm drill	ON	-0.1279	-0.3228	-0.1593	1.126	-0.4071	9.871
36284	15587422	10mm drill	ON	-0.1429	-0.3314	-0.1639	1.126	-0.184	9.905

However the x,z coordinates are not necessary in the process plan as the plan only requires the instruction. So this source of error is hidden.

Drill through hole Hole diameter 10mm	10mm diameter twist drill

Figure 50 Hidden errors

This information although not parsed into the plan was recorded in HAPP's log file which is illustrated in Figure 50 and the frequency of these errors in Figure 51. This indicates that some operators need further support with drawing interpretation.

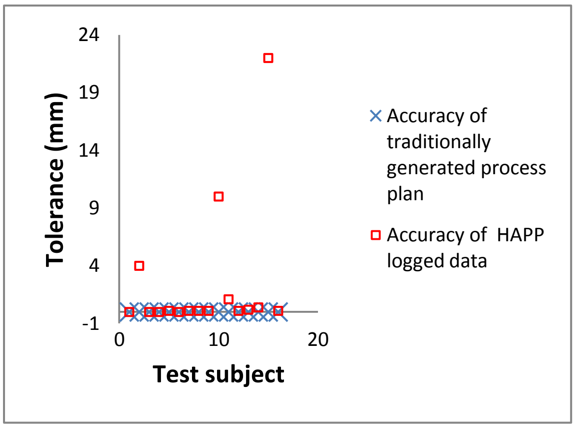


Figure 51 Process plan, errors, illustrated by inaccuracies.

6.7.2 Results for measures of efficiency

The TCTs for the traditional process planning environment and its component parts are presented in Figure 52. The TCT measured was the time taken to complete the task from start to finish, the MC is the physical motor aspect of recording the information which is either haptic manipulation in HAPP or writing in the traditional process plan and CC is the cognitive component, where the participant spends time thinking or strategising how to machine the part. The results are reasonably consistent with the exception of one outlier, Participant 9.

The large TCT recorded by this individual could be partially attributed to the length of process plan written.

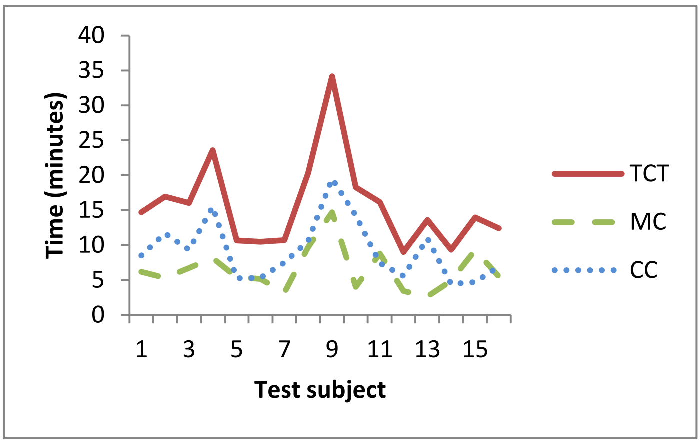


Figure 52 Time taken to complete the traditional planning task (task 1) separated into cognitive (CC) and physical motor component (MC)

The TCTs for the virtual planning environment and its motor and cognitive components are presented in Figure 53. Participant 15 had difficulty locating objects in the virtual 3D world as the 3D image 'kept inverting'. This made it difficult for this participant to select and position objects during the simulation.

Further analysis reveals that in a traditional planning environment, more time is spent on strategizing/thinking rather than recording the plan (Figure 52); whereas Figure 53 shows that in a virtual planning environment more time is spent recording the plan, than strategizing/thinking how to machine the part.

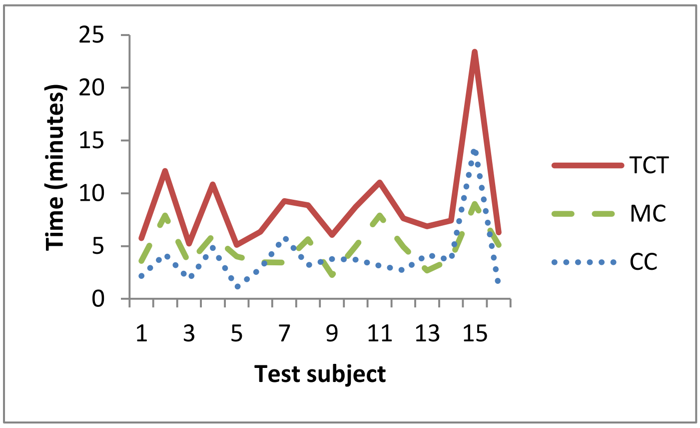


Figure 53 Time taken to complete haptic aided planning task (task 2) separated into cognitive and physical motor components

Figure 54 compares the TCT for Task 1 and Task 2.

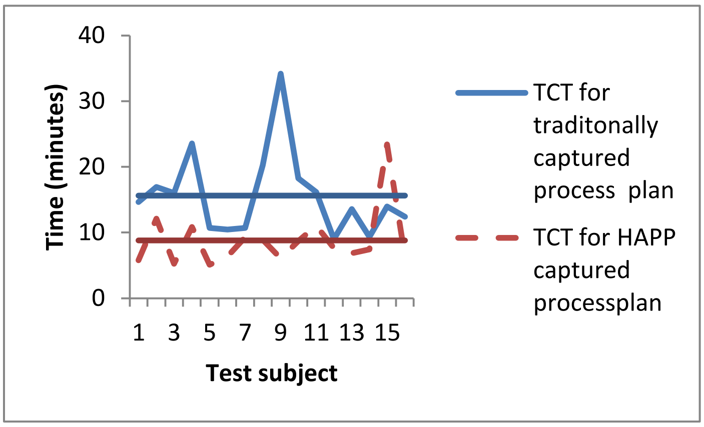


Figure 54 Task completion time for task 1 and task 2

It can be seen that the overall TCT is lower for the plan generated in the virtual environment (mean value 9 minutes) than that in the traditional environment (Figure 54) where the mean TCT is 16 minutes.

Figure 55 compares the time spent thinking in both environments.

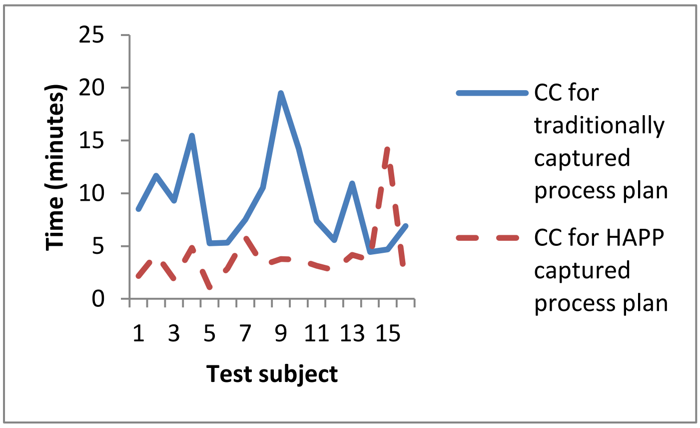


Figure 55 Cognitive component for task 1 and task 2

In Figure 55 the NULL hypothesis that the CC for both tasks 1 and 2 are the same fails a paired t-test. A paired t-test was used because the data was proven to be normally distributed by a Lilliefor test, the sample size was less than 30 and the same group carried out both tasks. This result indicates less time is spent thinking/strategizing in the virtual planning environment.

Figure 56 compares the time spent documenting information for both environments.

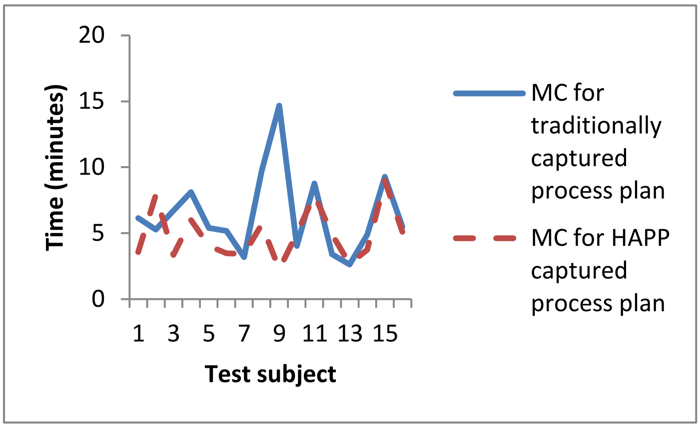


Figure 56 Physical motor component for task 1 and task 2

In Figure 56 the NULL hypothesis that the time taken in both tasks for the MC passed a paired t-test indicated there was no difference at this point in the time taken for the MC between Tasks 1 and 2.

Figure 57 approximates the learning curve for the HAPP software to generate the plan.

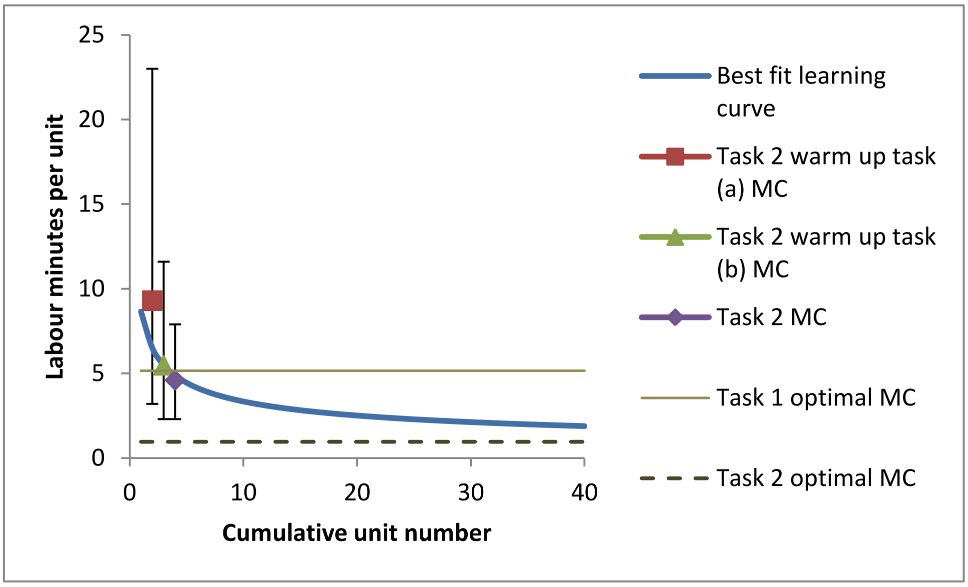


Figure 57 Best fit learning curve and optimal MC for task 1 and task 2.

Although the number of tasks carried out in the virtual planning environment was limited an expected learning curve of the motor effort could be approximated by finding the best fit through the average physical motor time to complete each task. The best fit curve was derived from the analytical model of task performance derived by Wright [150]. The optimal time for the motor component within the virtual system was calculated to be 57 seconds for an expert simulating the task. Although indicative, it is estimated that the average user should achieve close to this time within 40 operations of the software as shown in Figure 57. The optimal time for the motor component of task 1 was calculated by averaging the time taken by 12 participants, whose times followed a normal distribution, to copy an ideal process plan, which was 5 minutes and 9 seconds.

6.8 Subjective results

An evaluation of both systems for all sixteen users was carried out to establish HAPP's usability. To enable a closer securitization of the results different user group perspectives and abilities were considered, specifically prior experience in similar interactive environments such as computer games. The SUS score ranges from 0 (minimum) to 100 (maximum) [143] and is calculated by:

- Converting each user response to a value between 0 – 4.
- For positively worded items, this is achieved by subtracting 1 from the scale position.
- For negatively worded items, this is achieved by subtracting the scale position from 5.

- The converted responses are then added and multiplied by 2.5 to create a score ranging between 0 – 100. See Table 11.

System learnability scores were derived from item 4 and item 10 as defined by Lewis and Sauro [99]. Both items 4 (I think I would need the technical support of a technical person to be able to use this system) and 10 (I needed to learn a lot before I could get going with this system) are negatively worded so the value is calculated as in the normal calculation for the SUS score; 5 – the scale position for each question which is then normalized to a score between 0-100 by multiplying by 12.5. Thus a participant who was neutral about item 4 (5 -2) and neutral about item 10 (5-4) would assess the system as having a learnability rating of (2+2) x 12.5 = 50 out of 100. See Table 11.

Table 11 Example calculation of SUS and learnability scores

	Score	Converted score
Item 1	3	2
Item 2	4	1
Item 3	3	2
Item 4	2	3
Item 5	1	0
Item 6	5	0
Item 7	2	1
Item 8	1	4
Item 9	3	2
Item 10	4	1
Total SUS score		16
Normalised total (SUS score)		40
Total learnability score (Items 4 and 10)		4
Normalised learnability score		50

The results of the perceived usability and learnability of the HAPP and Traditional systems are shown in Table 13 and Table 14 with different SUS scores recorded for different user groups. Levels of expertise in process planning were classified by the individual users' logged hours in process planning training and application (Table 12).

Table 12 Classification of process planning expertise

Practical application of CAPP (hours)	Training in CAPP (hours)	Classification of Expertise
> 8	> 960	Expert
> 8	> 40	Intermediate
< 8	< 40	Novice

Table 13 SUS scores for process planning systems.

User Group	Sample size	SUS score (mean)	
		Traditional process planning approach	HAPP
All	16	43	70
Expert planners	6	64	57
Novice planners	8	35	78
High level of computer gaming experience	7	41	73
Low level of computer gaming experience	9	44	67

Raw data for the pilot study questionnaires can be found in the appendices in the section entitled Pilot Study Data.

Table 14 Learnability scores for process planning systems.

User Group	Sample size	SUS score (mean)	
		Traditional PP approach	HAPP
All	16	46	67
Expert planners	6	60	56
Novice planners	8	30	75
High level of computer gaming experience	7	38	71
Low level of computer gaming experience	9	53	64

Within a context of use set to be as close to an industrial working environment as practical, HAPP receives a SUS usability score of 70 and a learnability score of 67. An interpretation of this score derived from [144] indicates the HAPP system usability within a general context is a 'high OK' and falls within the acceptability range of 'acceptable'. The traditional approach to process planning only scores 43 (descriptively interpreted as 'poor') for usability and 46 for learnability. Therefore it can be seen that HAPP is perceived to provide a more learnable and usable approach to process planning.

A deeper analysis of perceived usability and learnability results was undertaken to investigate the possibility of any trends between the user groups that may create any bias based on user experience of either planning or similar interactive computer systems e.g. games.

The following graphs illustrate and compare the average responses to questions between systems and users. The average response for each item was calculated by the mean of the sum of the individual's answers for the particular item.

T-tests were used as the sample size was less than 30 which is normally required for a z test. Dependent t–tests were carried out for comparisons with the same user group and the data was found to be normally distributed. A Wilcoxon signed rank test was carried out where the data did not have a normal distribution. For comparisons across user groups an independent t-test was carried for normally distributed data with equal variance and a Wilcoxon rank sum test for non-parametric data. Data set normality was tested for using Lilliefors test and equivalence of variance by f-test. All statistical analysis was carried out at the 5% significance level.

6.8.1 User group – all

Figure 58 illustrates the SUS response for all users on both systems (N = 16). The NULL hypothesis that the SUS score for both systems should be the same was rejected by a dependent t-test carried out in MATLAB at the 5% significance level.

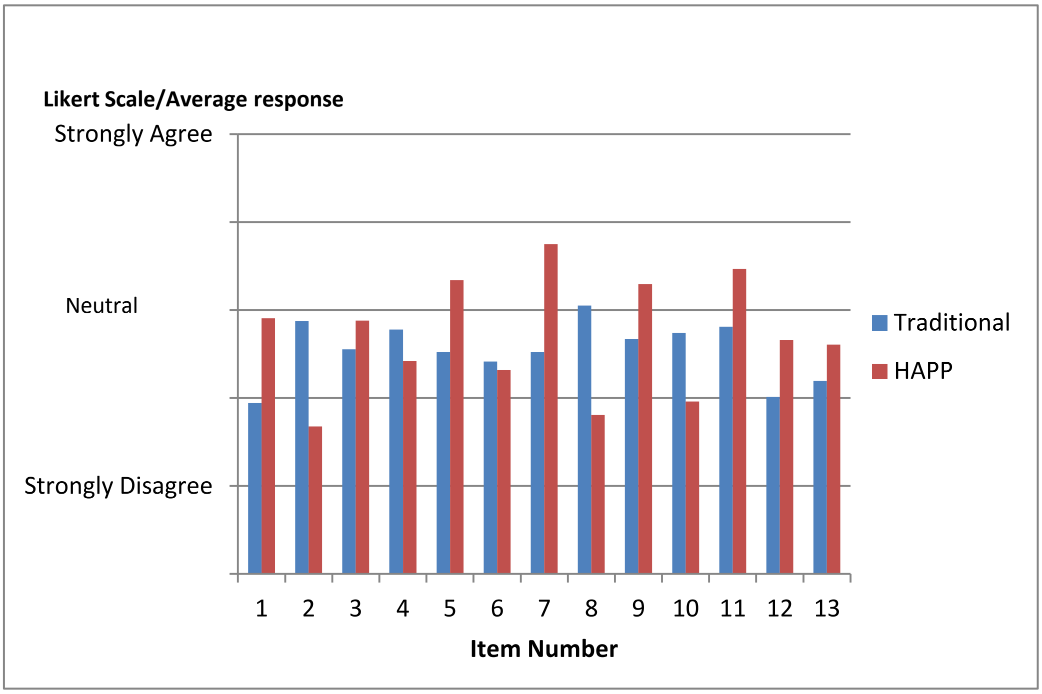


Figure 58 Usability questionnaire results, all users.

The NULL hypothesis, that the individual responses should be equal for both systems was rejected for questions 1, 2, 5,7,8,9,10,11,12 by the Wilcoxon signed rank test. These revealed:

- the users preferred to use HAPP more frequently;
- HAPP was less complex and the functions were better integrated;
- the operators felt HAPP would be quicker to learn and less cumbersome to use;
- the users also felt more confident in HAPP's operation, would need to learn less and were more immersed (as discussed in section 6.3 immersion can be linked to enjoyment) ;
- the users felt their mental workload was reduced using HAPP.

The results indicate that for all users HAPP was perceived to be more usable and learnable than traditional process planning approaches. The most significant differences were users felt they would learn to use HAPP quickly; it was less cumbersome and would like to use it frequently.

6.8.2 User group – by planning experience

Further analysis was carried out to understand how expert planners would react to a new approach for process planning in comparison to current approaches. In order for a new approach to be commercially viable it is important that experts see some benefit in order to accept any change. Figure 59 illustrates the results of the SUS Questionnaire given by the expert planners (N = 6). The NULL hypothesis that the SUS score for both systems should be the same was accepted by dependent t-test at the 5% significance level. The NULL hypothesis that the learnability score for both systems should be the same was also accepted by a Wilcoxon signed rank test at the 5% significance level.

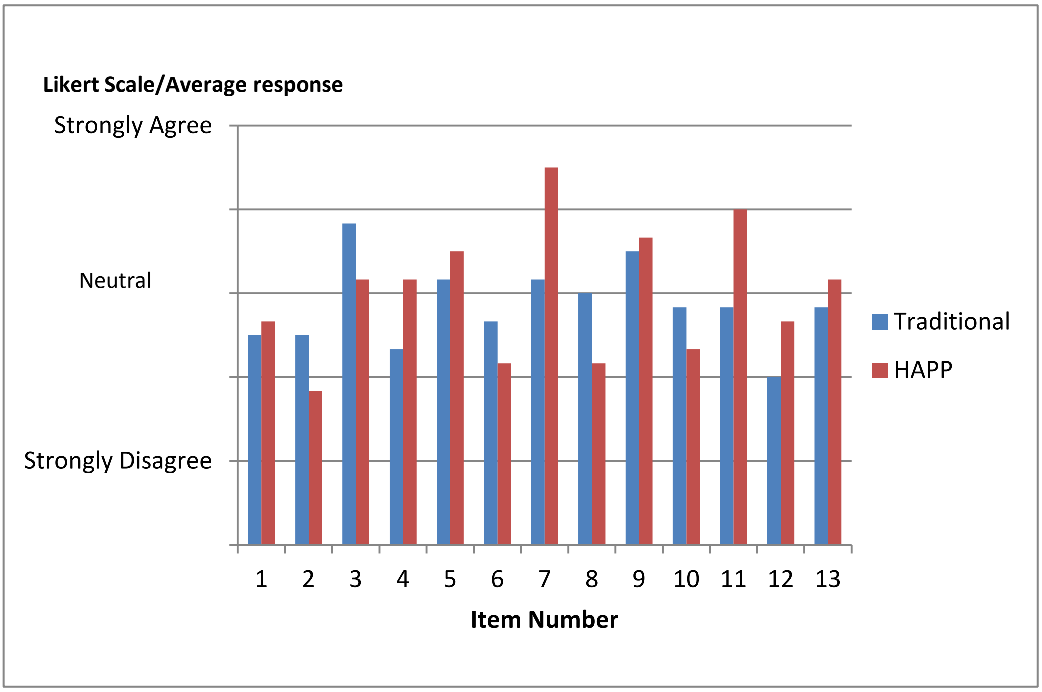


Figure 59 Usability questionnaire, expert planners.

A closer analysis of the results with regard to expert planners show that the most significant sample differences include questions 7 and 11, indicating that experts felt more strongly that users would learn to operate HAPP more quickly and also that they found HAPP more immersive. However these cannot be extended to a population with a 95% confidence level.

It is interesting to see that initial indications show that expert users did not perceive the virtual environment to be any worse than the traditional environment. This is encouraging since the VR approach is still in its infancy and should improve as underlying issues are further understood using evaluation methodologies as defined in this research. However, applying HAPP to more complex part geometries would be an interesting further study.

In contrast to expert planners Figure 60 compares the feedback from the novice process planner user group (N=8) for both systems. It is important that new planners also find advantages in new approaches and that new systems do not only target planners who are already highly skilled. The NULL hypothesis that the SUS score for both systems should be the same was rejected by a dependent t-test at the 5% significance level. The NULL hypothesis that the learnability score for both systems should be the same was rejected by a Wilcoxon signed rank test at the 5% significance level.

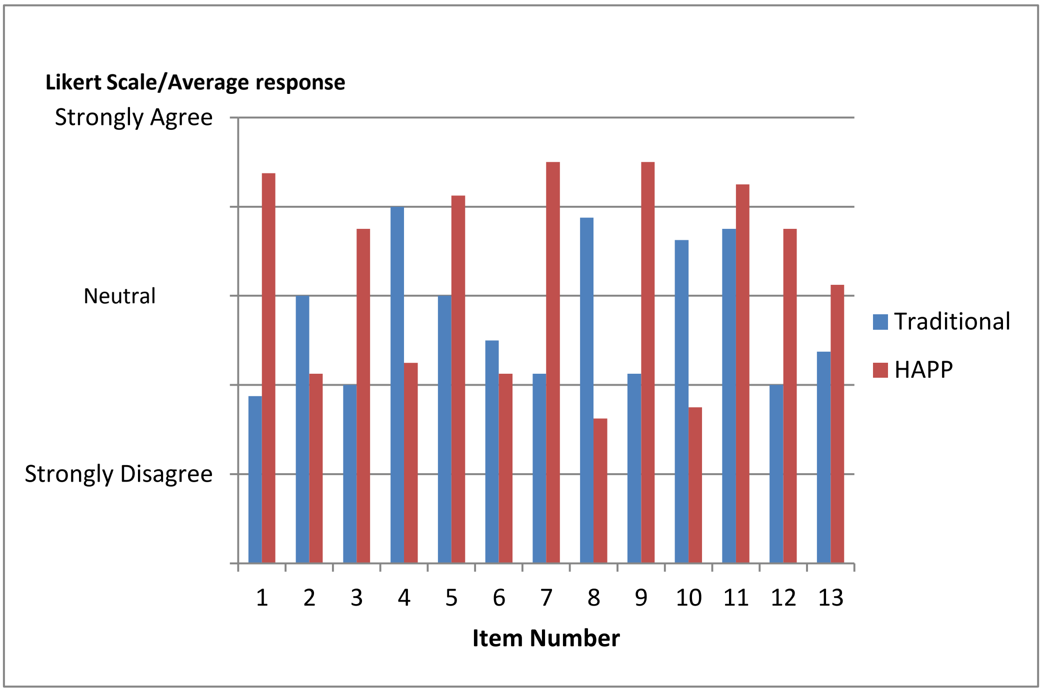


Figure 60 Usability questionnaire, novice planners.

Questions 1,3,4,7,8,9,10,12 showed significant statistical differences (Wilcoxon signed rank test):

- indicating novices would like to use HAPP frequently;
- HAPP was easier to use;
- HAPP would need less technical support;
- most people would learn to use HAPP more quickly;
- found HAPP to be less cumbersome;
- felt more confident using HAPP;
- would need to learn less before using HAPP; and
- HAPP required less mental workload.

These results show that novice planners find HAPP to be both more usable and learnable. Interestingly they also felt more confident in HAPP. This supports the findings in the literature review where VR is reported to improve the understanding of complex processes (3.3.1).

6.8.3 User group – by level of computer game experience

One limiting factor in the industrial use of CAPP systems is the level of IT skills required to operate a system, Figure 61 and Figure 62 examine if there is a link between the users perception of the two systems and their level of computer gaming experience. Figure 61 compares the two systems from the perspective of a user with a high level of computer gaming experience (N = 7). The NULL hypothesis that the SUS score for both systems should be the same was rejected by Wilcoxon signed rank test. The NULL hypothesis that the learnability score for both systems should be the same was accepted by Wilcoxon signed rank test.

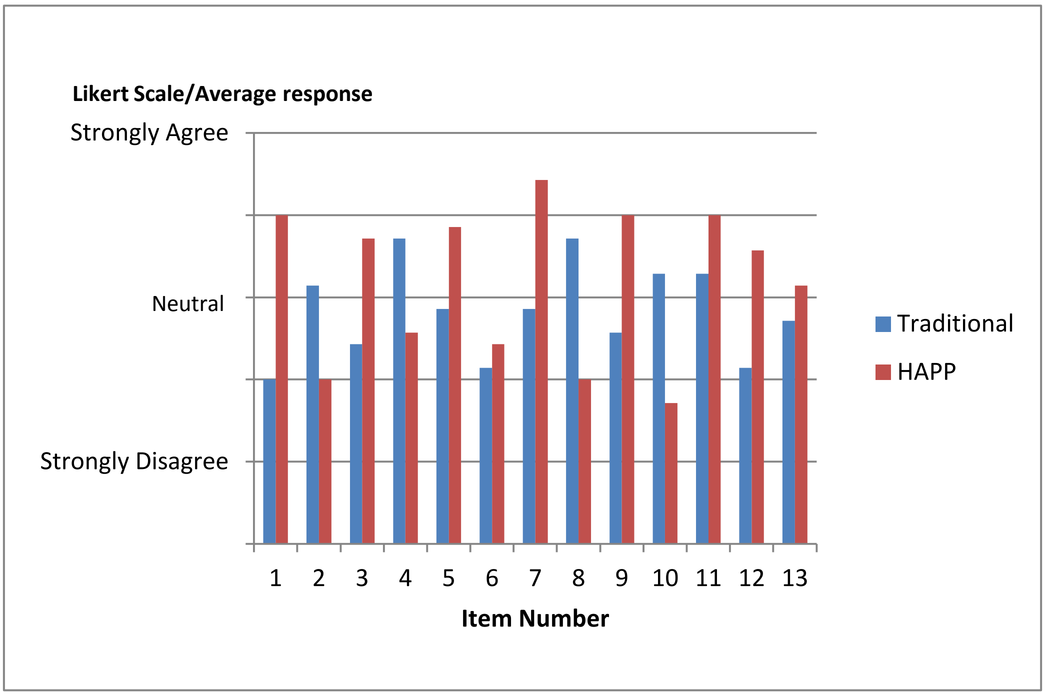


Figure 61 Usability questionnaire, users with more than 800 hours computer game experience.

A comparison of the results reveals that only Question 1 is statistically significant (Wilcoxon signed rank test). Indicating that users with significant computer gaming skills would prefer to use HAPP more often.

These results confirm that users with high levels of gaming experience find HAPP to be more usable than the traditional planning approach and that would prefer to use HAPP more frequently.

As the level of IT skills was reported to be an issue with current CAPP systems it is interesting to evaluate how users with low levels of computer gaming experience find this CAPP system in comparison to conventional methods. Figure 62 compares the two systems from the perspective of users with less than 200 hours gaming experience (N = 9). The NULL hypothesis that the SUS score for both systems should be the same was rejected by dependent t-test. The

NULL hypothesis that the learnability score for both systems should be the same was accepted by Wilcoxon signed rank test.

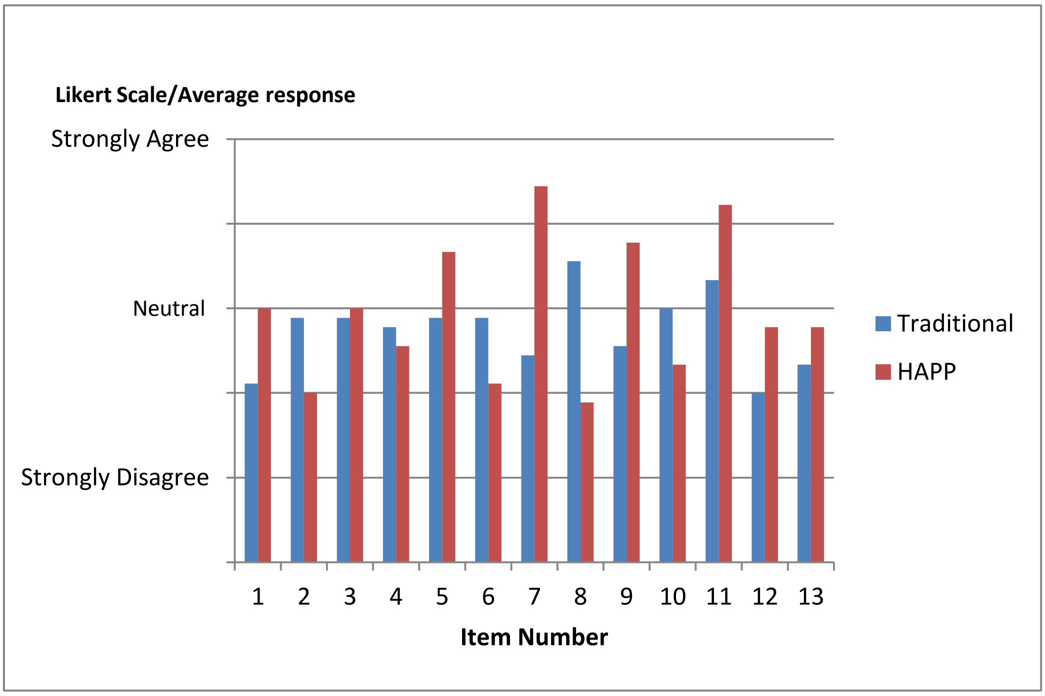


Figure 62 Usability questionnaire, users with less than 200 hours computer game experience.

With regard to individual questions, questions 7 and 8 reject the NULL hypothesis at the 5% significance level, indicating a significant difference (Wilcoxon signed rank test) such that participants thought HAPP was less cumbersome to use and thought users would learn to use the system more quickly.

An analysis of the results reveals that users with low levels of computer gaming experience also found HAPP to be a more usable system. This demonstrates that a low level of computing skills will not prevent users adapting to HAPP.

Most young people in the future will have experience of game interfaces so it is probable that systems such as HAPP would supplement their learning experience better than CAPP systems. This research clearly demonstrates that users with high and low levels of computer gaming skills showed a preference for HAPP.

6.8.4 Comparison of novice and expert planners perception of virtual planning task

Comparing novices and experienced planners perception of HAPP will enable a clearer understanding of which user group receives the most benefit from the system and help prioritise future development. Figure 63 compares the novice and expert users' perceptions of the haptic virtual planning environment (N=16). The NULL hypothesis that both user groups should rate the system the same with an equivalent SUS score is rejected by an independent t-test. The NULL hypothesis that novices and experts found the virtual system equally learnable was accepted by Wilcoxon rank sum test.

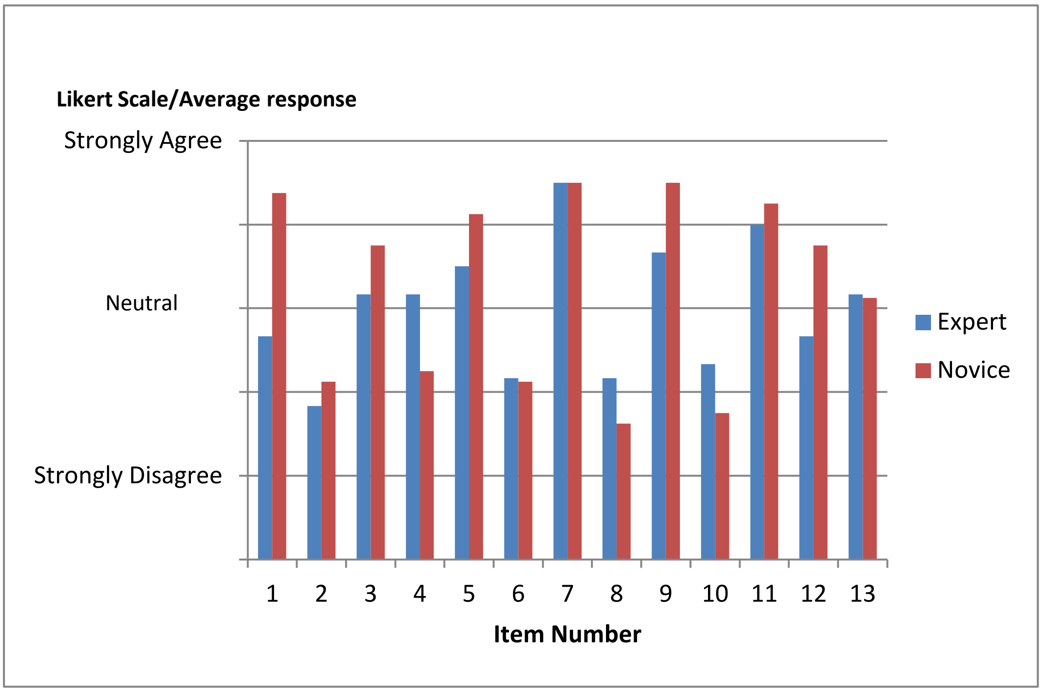


Figure 63 Novices and experts perception of virtual planning task.

For individual questions only question 1 was found to reject the NULL hypothesis at the 5% significance level, that the Likert response should be the same for both user groups. This question refers to how often a user would like to use the system and it can be seen the novice planners indicated they would like to use the system more often than the expert planners.

The results demonstrate that novice planners find HAPP more usable than experienced planners but only one question, question 1 shows a significant difference. The difference in the assessment of usability cannot be attributed to any specific SUS question but it is worth noting that novice planners felt more confident than expert planners using HAPP.

6.8.5 Comparison of novice and expert perception of traditional planning task

In order to develop a new process planning approach it is important to understand the limitations of existing approaches. By comparing novice and expert planners' assessments of a traditional process planning approach the limitations of the traditional PP approach from a novice's perspective can be understood. Figure 64 compares the novices and experts' perception of the usability of the traditional process planning approach (N=16). The NULL hypothesis that both user groups should rate the system the same with an equivalent SUS score is rejected by an independent t-test at the 5% significance level. The NULL hypothesis that novices and experts found the traditional system equally learnable was accepted by Wilcoxon rank sum test at the 5% significance level.

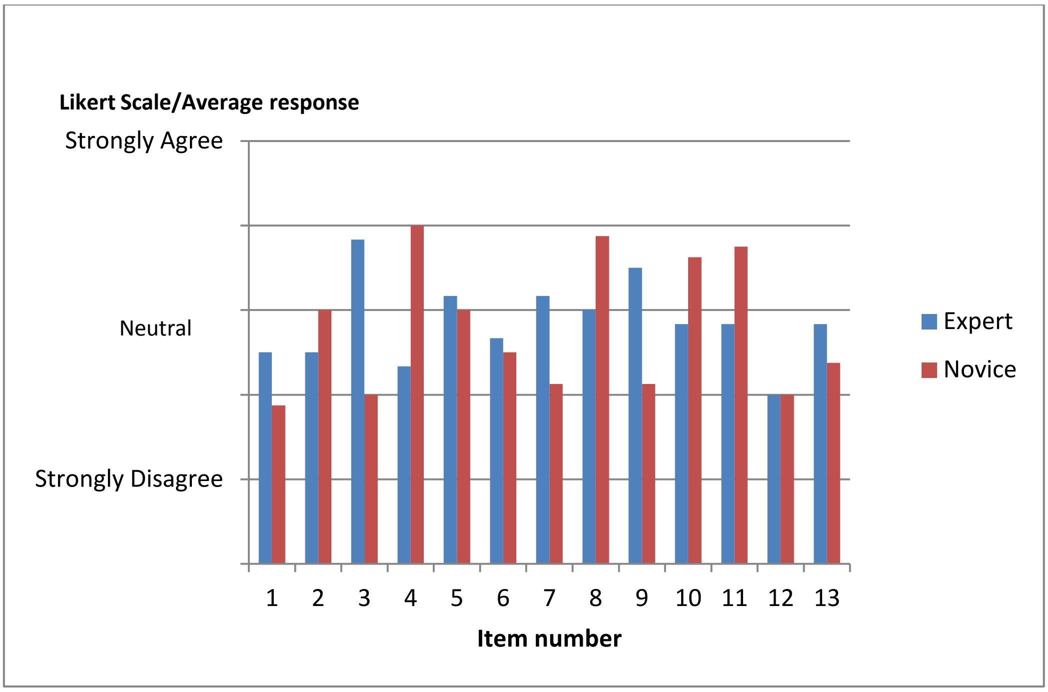


Figure 64 Novices and experts perception of traditional planning task.

It was found that questions 3, 4 and 9 had statistically significant differences i.e.:

- experts felt the traditional method was easier to use than the novices;
- they would need less technical support and
- were more confident.

This is probably due to the fact that experts do not need the visualization of the environment at this level of difficulty of machined product and they are also confident in their knowledge of methods feeds and speeds and do not need computer assistance to generate these. It appears that traditional approaches rely more on the planner's experience and do not provide sufficient support for novice planners.

6.8.6 Comparison of user groups perceptual measure of virtual planning task by computer gaming experience.

Skill levels with similar interactive environments may affect the users' perception of HAPP. Figure 65 contrasts users perception of HAPP usability between users with a lot off computer gaming experience and users with little computer gaming experience. The null hypothesis that both user groups should rate the system the same with an equivalent SUS score is accepted by an independent t-test at the 5% significance level. The null hypothesis that users with and without computer game experience would find both systems equally learnable was also accepted at the 5% significance level.

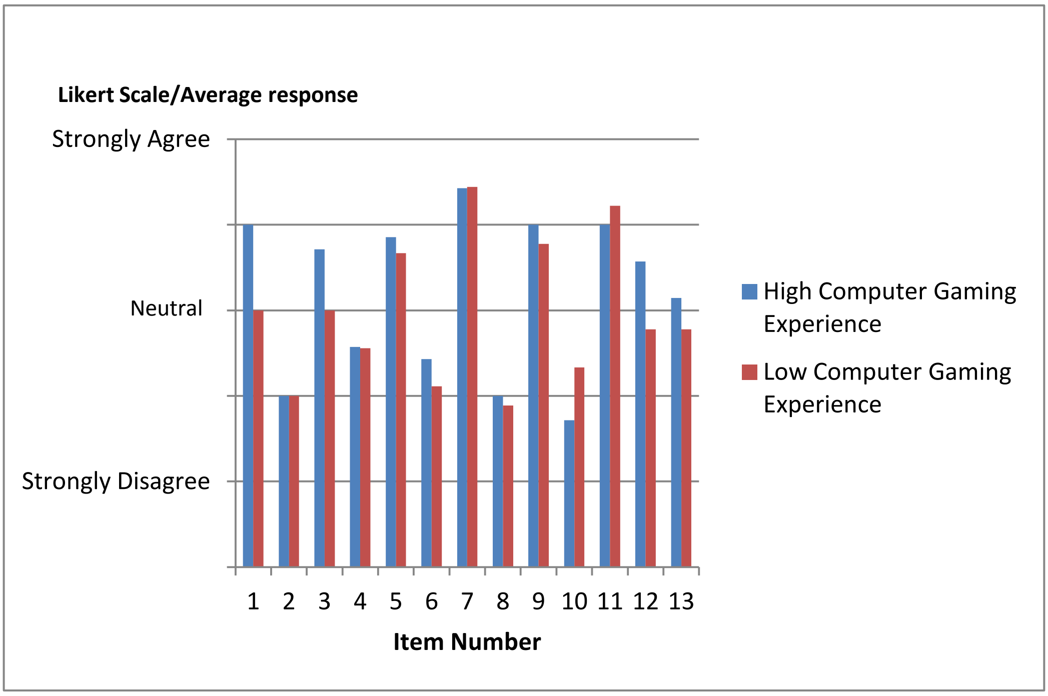


Figure 65 Users with and without computer gaming experience perceptual measures of virtual process planning.

The null hypothesis that both user groups would return the same score for individual questions was accepted by Wilcoxon rank sum test.

In a direct comparison of users with differing amounts of computer gaming skills, it was found that neither group found the virtual system more usable or learnable than the other. This is interesting as it provides an early indicator that users both with and without highly developed skills of operating in 3D virtual environments will be able to operate the system effectively.

6.8.7 SWOT analysis

In conjunction with the questionnaire each user was asked to complete a SWOT analysis of the HAPP environment to help understand the root cause of any usability issues (Table 15) in order to define future areas for improvement. This was also supplemented by some observed data and remarks made by the participant during an interview. A SWOT analysis was not required for the traditional planning approach as it was applied here to gain a deeper understanding of the reasons why a system is perceived as it is in order to drive future development.

Table 15 SWOT analysis of HAPP (number of times point was commented on).

Strengths	**Weaknesses**
• Ease of use (4) • Provides nice feedback (1) • Simple to learn and understand (2) • Good visualization aids planning activity (6) • Fun (3) • Interactive (1) • Can prototype (4) • Safe prototyping (1) • Faster than physical prototyping (1) • Cost effective - no down time for real machines (1)	• Physical modelling not accurate enough (5) • Difficult to position object accurately (4) • Occasionally object gets stuck (3) • Using lower case or upper case of the same key for locking axis and zeroing axis is a bit confusing (3) • Easy to select and move wrong object by mistake • Depth difficult to perceive (2) • Relies on good eye hand coordination (1)
Opportunities	**Threats**
• Teaching and training (5) • An intuitive means of solving inverse kinematic issues (1) • Robotic arm simulation (1)	• Existing simulation software (2) • Price? (1) • Industry inertia to move to new approaches (1) • Working in a 3D environment all day might be quite straining on the eyes (1) • Haptic generated forces could get tiring (4)

A root cause analysis of the perceived weaknesses includes issues such as inter body penetration, accurately positioning objects with only hand-eye coordination, keyboard mapping and depth perception. Even though the system achieves a perceived usability rating as a 'high OK'; reasons can be identified in order to make further improvements. However, the same analysis finds that the strengths of HAPP include easy to use and learn, immediate feedback and that visualization aids the planning task. These strengths are the underlying reasons that can be attributed to the efficiency of the system, in particular the reduced cognitive load. It is likely that the ease of use, improved visualization and immediate feedback all combine to reduce the amount of time a planner needs to think and strategize about how to plan a machining sequence in HAPP.

6.9 Discussion of the evaluation method

The evaluation method works reasonably well for a number of reasons:

- It allows a fair comparison of different process planning systems.
- These systems can be platform independent.
- It evaluates user satisfaction;
- The efficiency of the system with regard to a user's cognitive requirement.
- The efficiency of the system with regard to a user's motor-physical requirement.
- The effectiveness of the system output with regard to a quality of information.

Not only does it capture the state of how well a system performs but with the application of a SWOT analysis it also aims to identify underlying reasons for this state. However in the current application of the evaluation method some aspects of the effectiveness are fairly localized and are not applied to the output as a whole. A more widely applied implementation would be more effective allowing not just an insight to the system effectiveness but an overall measure. Further improvements could also include an objective measure of the system learnability to support the perceived system learnability and a practical validation of the theoretical evaluation of the system effectiveness.

6.10 Conclusion

With regard to the subjective data captured the questionnaires have provided a measure of the perceived usability and learnability of the haptic process planning environment with the application proving to be more usable and more learnable than a traditional process planning environment. A specific user group - the novice process planners, however skew the results since it would appear that the rich, graphical, simulated environment and the ability to assist with the generation of detailed information, such as feeds and speeds, brings confidence to inexperienced process planners. This can be considered to be evidence of the information promotion through better understanding, expected to be seen as part of using a virtual environment (3.3.1). However, it was also reassuring to see that experienced process planners could easily migrate towards a virtual system without the need for developing new IT skills;

since it appears that operators with and without large amounts of experience in similar but non-haptic interactive environments could also navigate the system easily. This is important since one of the reasons cited for not adopting current CAPP systems was the need for training, which is probably mainly associated with poor interfaces.

For the objective analysis, a method for measuring the quality of output of a planning system has been proposed which has a means of measuring the physical and cognitive efficiency of a system. The results confirm that when compared to traditional process planning the HAPP system, reduces the mental workload of a process planner, produces better quality data and enables plans to be generated more quickly. This meets the aim of the experiment to unambiguously compare the usability aspects efficiency and effectiveness of a VR-based haptic process planning environment to a more commonly used traditional process planning approach by taking objective measures.

A summary of the outputs of this part of the research is given in Table 16.

Table 16 Summary of comparison of HAPP and a traditional PP system

	Most highly rated in individual aspects of usability measures					**Most 'usable' system overall**
Satisfaction						
	HAPP					HAPP
Effectiveness	Conciseness	Clarity	Consistency	Completeness	Accuracy	
	HAPP	HAPP	HAPP	HAPP	HAPP[4]/ Traditional	HAPP
Efficiency	Strategizing	Documenting	Overall			
	HAPP	HAPP[5]	HAPP			HAPP

6.11 Summary

In Chapter 6 HAPP was improved to include a stereoscopic visual interface and the user control of the point of view constrained to four view points. The evaluation method was elaborated based on the more formal criteria of usability as defined in ISO 9241-11. The method was

[4] Plan is accurate however logged positional data may not be as accurate as drawing, this is because of noise caused by operator eye hand coordination.

[5] Only as operators become more experienced with system. This is expected to be within 10 operations in accordance with Figure 57

applied not only to HAPP but also to one of the most commonly used approaches to process planning, the traditional approach, in order to provide a benchmark and quantify the advantages/disadvantages of HAPP.

The results of the evaluation of each system was compared and contrasted and any conclusions statistically validated where relevant, thus meeting research objective 3."The cross comparison of the two systems and the statistical analysis of any output ensuring robust results."

Overall HAPP was found to be more effective, efficient and achieved a higher level of perceived satisfaction than the traditional process planning environment, thus answering research question 3 "How does a haptic process planning environment compare to a commonly used process planning approach with regard to satisfaction of use, efficiency and effectiveness?"

In this chapter it was highlighted that for industrial acceptance it is important that the system be accepted in a commercial environment and that currently experienced planners perceive the least benefit. This leads to a further round of system improvements which will be evaluated in an industrial trial, specifically targeting the user group that perceived the least benefit. System modifications should address identified issues including system efficiency and effectiveness by providing better support for object positioning and capturing better feature descriptions.

Chapter 7 Industrial trial

7.1 Introduction

From the findings in Chapter 6 it was revealed that the expert user group found HAPP to be less usable than the novice user group. It is possible that the test cases were too trivial for the former user group. In the third iteration of HAPP, the issues identified in the previous round of testing are addressed and further functionality added to allow more detailed industrial trials. The systematic approach to evaluation from the previous chapter is taken forward and improved to provide a more complete evaluation. The third version of HAPP is then compared to the previous version in order to ensure improvements are valid and to address the research objectives and research questions with regard to the overall aim and hypothesis.

7.2 Industrial trial purpose

The purpose of this stage of the research is to address any areas of weakness identified in the pilot study, update the evaluation method based on any issues highlighted and to verify that the automatically generated process plans are in fact usable. The same research questions and objectives will be addressed as in the pilot study; except that HAPP will be compared to its previous version with more complex tasks being carried out. This will ensure the new revision is still 'usable', is building on the previous work, evaluating whether or not HAPP is relevant to expert users.

7.3 HAPP system modifications

Based on the pilot study several areas of improvement were identified and incorporated into HAPP:

1. The requirement to aid the user with drawing interpretation was derived from the inaccuracies found in the haptic log files, indicating operators had misinterpreted the drawings and drilled holes in the wrong position.
2. Haptic support was added to aid the positioning of a manipulated object, this was derived from observing the operators struggle to position a tool accurately by hand in advance of cutting.
3. Better functionality to define and capture machinable features was provided. The inability to capture clear descriptions of machinable features was revealed in the results with regard to system effectiveness where the output plan was found to be overly concise and incomplete in comparison to the ideal plan.

It was also felt necessary to extend the system functionality by incorporating the ability to machine more complex products. This would enable evaluation tasks more suitable to the 'expert' user group which, as identified previously found less benefit in HAPP than the 'novice' user group. This included:

1. The ability to carry out turning operations.
2. The ability to machine objects on multiple faces.
3. The ability to capture the plan in a more information rich environment for later analysis and review.
4. The replacement of set up clamps, bolts and blocks were replaced with more commonly used toggle clamps in the fixture library.

An updated system specification is shown in Table 17.

Table 17 HAPP version 3 updated specification

	HAPP	Description of how HAPP meets specification.
Process planning essential requirements		
Drawing interpretation and material evaluation.	x	**The final model is suspended in a translucent model of the raw material** and rendered on the monitor in 3D. The operator can manipulate the viewpoint through 4 set viewpoints by keyboard macros.
Process selection and sequencing.	x	The operator can select either **a centre lathe** or 2.5D milling machine in any order they choose.
Machine selection and operations sequencing.	x	The operator can manipulate the billet and cutting tools to carry out cutting sequences in any order they choose with the haptic device **The tools can be positioned on the haptically rendered final model suspended in the translucent billet** and locked in position prior to cutting by keyboard macros. **Cutting or turning can be carried out on multiple faces.**
Tooling selection.	x	A 5mm drill, 10mm drill ,16mm slot mill or **a right handed knife edge tool** can be selected with the haptic device. Tool access can be verified before a cutting sequence is started.
Setting the process parameters.	x	Process parameters will be automatically included from set values in the Machinery handbook.
Calculate machining times	x	Times will be calculated from standard equations.
Determining the work holding requirements.	x	A machine vice and clamp set will be included to enable the operator to plan the set up before machining. These will be manipulated through the haptic device.
Calculate set up time	x	The set up time will be calculated for the set up simulation.
Selecting quality assurance methods.	x	A virtual CMM probe will be included to measure material removed.
Documenting the process plan.	x	Process plans as described in [3] [5] will be generated automatically after the planner has finished simulating the machining sequence.
Costing the plan.	x	A cost is automatically generated with the process plan based on an hourly rate multiplied by the set up and machining times.
Process planning desirable characteristics specific to user		
Involve user in some part of the decision making process	x	All processes are carried out by an operator and specialist knowledge will be unobtrusively logged.
Include a user friendly interface	x	A haptic VR interface will be implemented.

An updated illustration of the system architecture is given in Figure 66, areas where the code has been modified are highlighted.

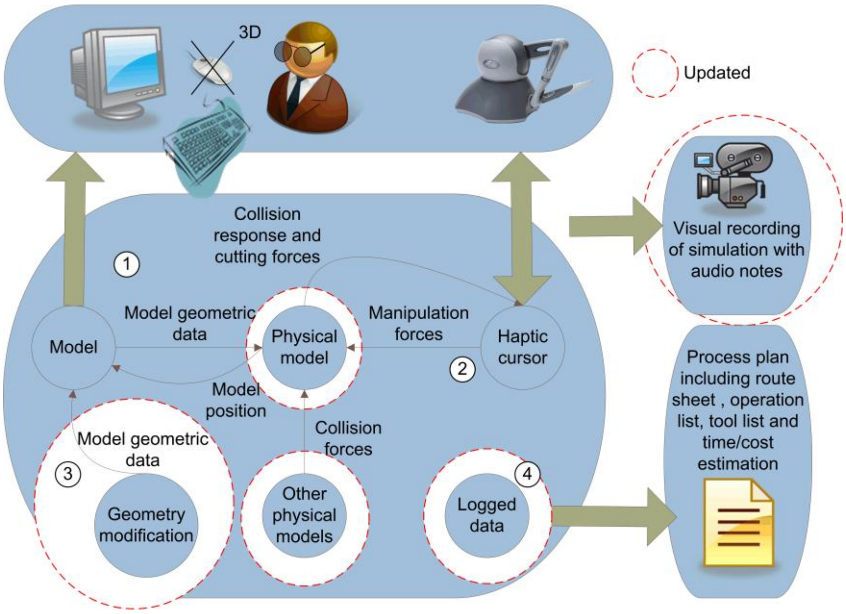


Figure 66 HAPP version 3 system architecture

7.3.1 Drawing interpretation aid

In order to aid the operator with drawing interpretation, the model of the component to be machined is rendered inside the billet and the billet surface made transparent (Figure 67). This aids a planner as they receive strong visual hints as to the location of features to be machined reducing the time they need to study and check against the drawing of the part to be manufactured. They can also datum their final cuts against the final component geometric features.

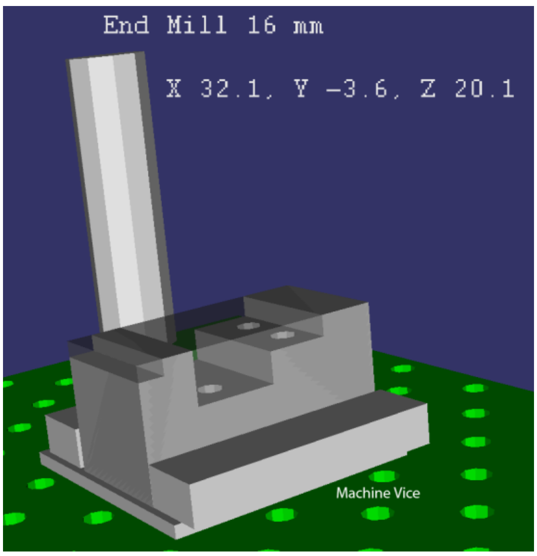


Figure 67 Translucent billet with haptically rendered model suspended inside

7.3.2 Improved haptic support for object positioning

It was observed during the pilot study that operators found the positioning of a tool by hand and eye quite difficult, in spite of the virtual fixtures that allowed individual axes to be locked. It was thought a tracing approach would be more efficient. Once a tool had been zeroed against the transparent billet, the collision response between the billet and tool was disabled. This allowed the participant to trace around the 3D model gaining haptic support for tool positioning before the tool was locked for machining position.

7.3.3 Machinable feature capture

The ability to capture a description of the type of feature being machined was added to improve the effectiveness of the process plan by creating more complete instructions. For example the instruction '*Mill slot, depth 25mm'* can be captured as opposed to *'Mill depth 25mm'*. This was achieved by embedding voxels of 1mm diameter in the tool tip and capturing which voxels intersect the billet during material removal. An advantage of the voxelated tool tip approach is that it is the machined feature which is captured and not the model feature. For example in component HWEPS06 (Figure 76), the model feature appears to be a slot with two shoulders, however in order to machine this part different features can be machined in a different sequence e.g. the machined features in sequence could be '*cut wide slot'* followed by '*cut deep narrow slot*' or '*cut deep narrow slot* ' followed by '*cut shoulder* ' and '*cut shoulder'.* The voxelated tool tip will allow the type of machined features to be captured and not the type of feature interpreted from the model. Further, the dimensioning of the cut is related to the orientation of the billet, for example in component HWEPS0010 (Figure 77) if the billet is clamped in a vertical orientation the machining parameters are recorded as cut depth 10mm, width 3mm; however, if the object is machined in a horizontal orientation the depth will be 3mm and the width 10mm (Figure 68).

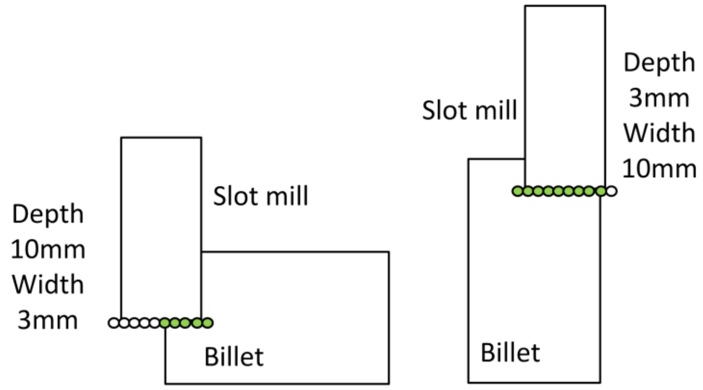


Figure 68 Captured feature dimensions

This approach accurately captures and describes the machining strategy as intended by the planner. With regard to milling the current system can identify features including slot, shoulder and face. Drilling features that can be recognised include through holes or blind holes. Turning features include facing and turning an outside diameter. An illustration of the voxelated tool tip for the slot mill is shown in Figure 69 and Figure 70 with some of the voxels rendered for illustrative purposes along with a graphical representation of features that can be captured by the system with the different tools.

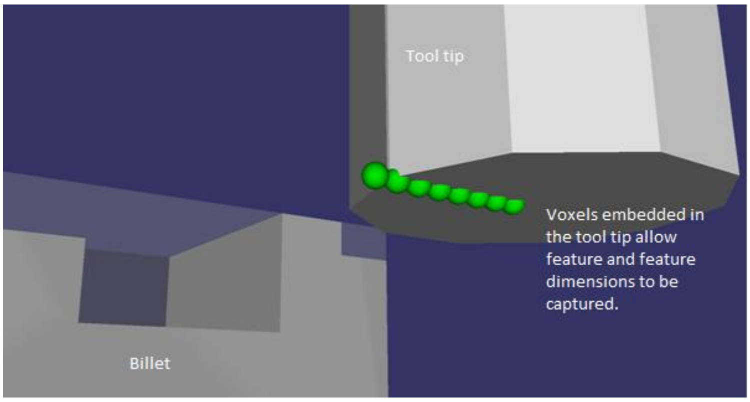


Figure 69 Voxelated tool tip

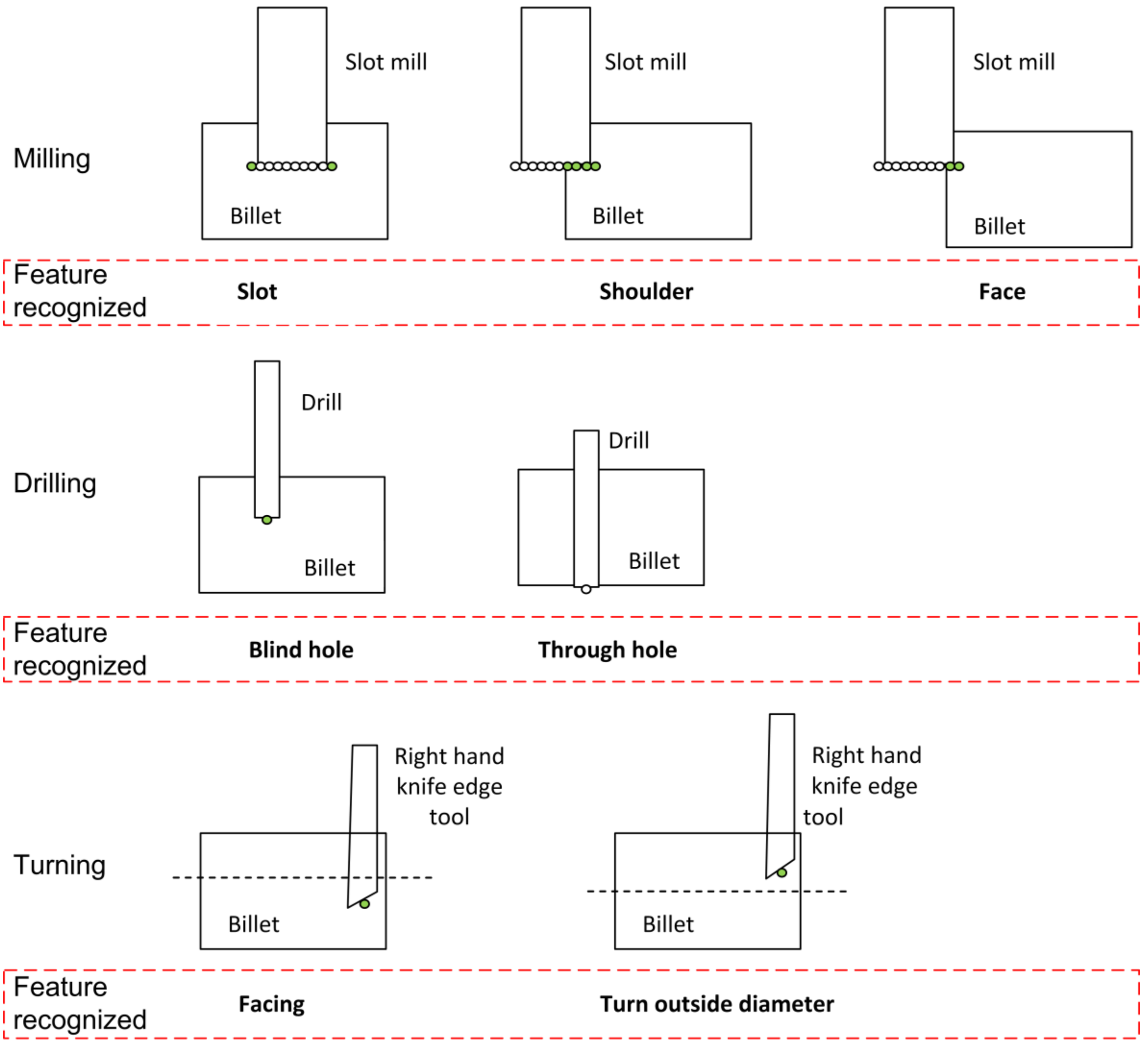


Figure 70 Voxelated tool tip with illustrations of recognisable machined features with associated tools.

7.3.4 Information rich data capture and review facility.

In order to capture information in a richer format a screen and audio capture facility was added to the system, this idea was drawn from the literature view where [75] captures assembly knowledge for planning, review and training in the form of video clips. This was implemented through freely downloadable screen capture software used to record the virtual simulation along with audio notes added by the operator [151]. This can be used to evaluate captured knowledge more easily (Figure 66).

7.3.5 Turning operations

The turning operation includes a right hand knife edge tool and a 4-jaw chuck. When the tool is selected the part is automatically loaded into the chuck, which is represented visually by a large disk (Figure 71).

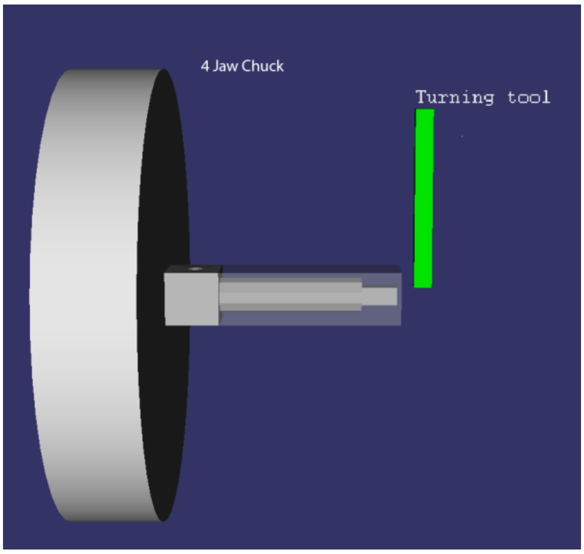


Figure 71 Turning operation

The right hand knife edge tool is constrained to the vertical and longitudinal axis and it is possible to carry out facing and turning of the outside diameter operations. Material removal for turning is carried out in a similar manner to milling in the sense that real time and delayed time approaches are taken. However, the implementation is different. To render material removal in real time the following steps were taken: (a) When the turning tool is turned on, the final turned geometry diameter is captured and rendered inside the billet. (b) As the tool is advanced along the billet, the billet length is reduced revealing the newly machined geometry. The material removal algorithm implemented in delayed time involves the generation of a swept volume with a variable sized aperture, which is not rendered. The length is calculated from the tool start and stop positions and the aperture size based on the tool depth at the start position. (c) The swept volume is then subtracted from the billet geometry to create the final machined object. An updated illustration of both the real and delayed time material removal process is shown in Figure 72 for all available operations.

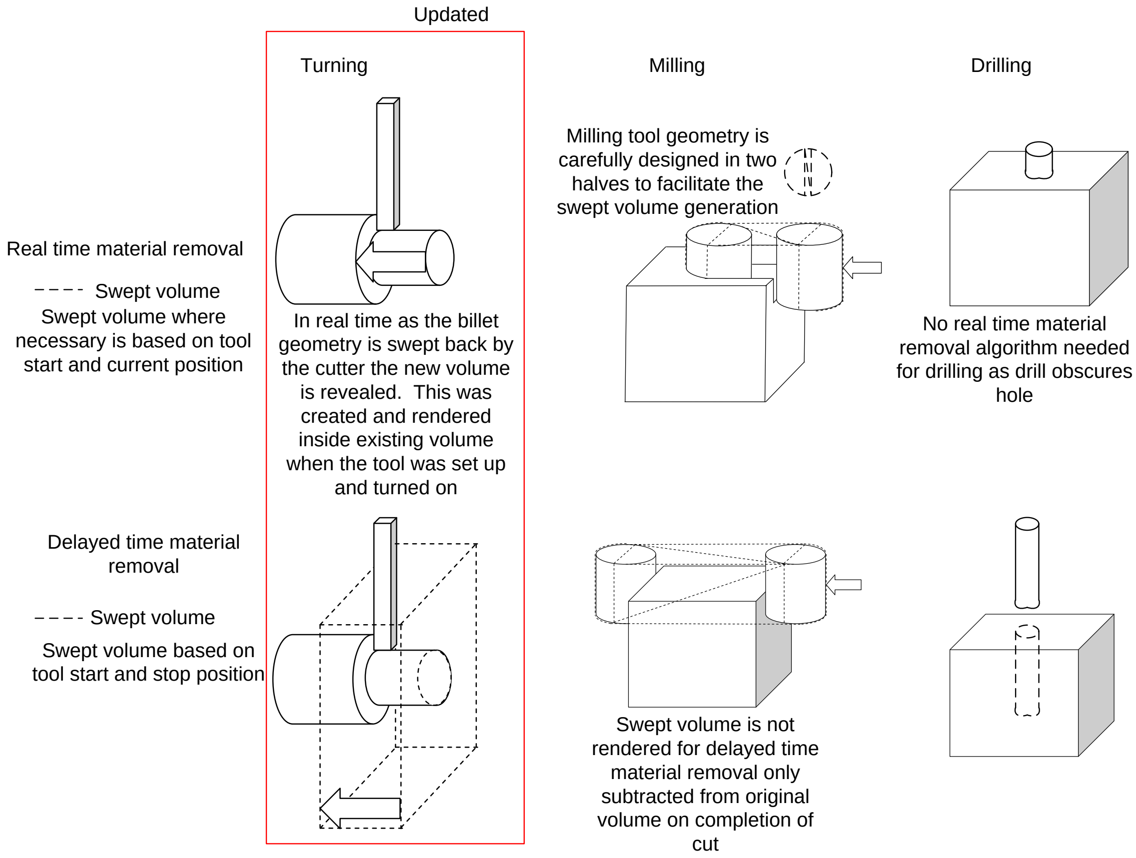


Figure 72 Swept volume illustrations

7.3.6 Machining of multiple faces

In order to carry out machining on multiple faces the rotational position of the haptic device is captured and applied to the manipulated billet. Manipulating and rotating objects in non-haptic based systems can be quite time consuming since generally one axis is selected at a time and the object rotated using a mouse: a haptic device is much more effective for this type of manipulation as it has 6DoF that can be mapped onto the manipulated object. However, as the feedback of the phantom-omni haptic device is limited to 3DoF, no rotational feedback can be felt by the user. This makes it more difficult to place objects flat. One solution could be to drop them and allow them to settle flat due to gravity. However, in this instance, gravity has no effect on objects when they are released since they default to a static state. For this reason a snapping to vertical and horizontal planes algorithm was added. An object can be manipulated and rotated as normal but when it is released it snaps to a vertical or horizontal axis. This algorithm operates on the rotational matrix of the object. The rotational matrix is accessed through a quaternion representation which represents an axis and the amount of rotation around that axis. The algorithm checks the value of rotation about a particular axis, in radians and either rounds it up, down or sets it to zero. This is carried out for each axis; a representation of the code for one axis is given below where bilq is the billet quaternion:

```
if(bilq[0]>0.2)bilqRounded[0] = ceil(bilq[0]);
else if (bilq[0]< -0.2)bilqRounded[0] = floor(bilq[0]);
 else bilqRounded[0] = 0;
```

7.4 Evaluation method modifications

Three changes were made to the evaluation methodology:

Firstly an objective measure of learning was added. This was achieved by repeating the warm up task several times. At each repetition the physical motor component, derived from the TCT was captured, it is the change in this which provides an objective measure of learning.

Secondly more thorough measures of effectiveness were implemented. These are now applied to each element of the process plan; the route sheet, operations sheet and tool list. This allows a more detailed look at the quality of the formalized information. Furthermore, one of the measures used as a measure of effectiveness was consistency. The measure of consistency for the previous test was derived from the feeds and speeds generated by the different systems. HAPP was shown to be more consistent in this aspect, as would be expected by a semi-automated system. However as the system was extended to include more complicated examples it was considered reasonable to extend the measure of system consistency to include the phrasing of instructions and strategy. At this point HAPP was tested with regard to how it copes with different examples of processes and was not being compared to traditional planning systems.

Thirdly, as highlighted in the evaluation of the test methodology in the previous chapter, a practical validation of the plans on the shop floor was required to check if the plans generated were actually usable.

The finalised formal approach for usability in CAPP systems is entitled the 'Usability Evaluation Method for Process Planning Systems (UEMPPS),Figure 73.

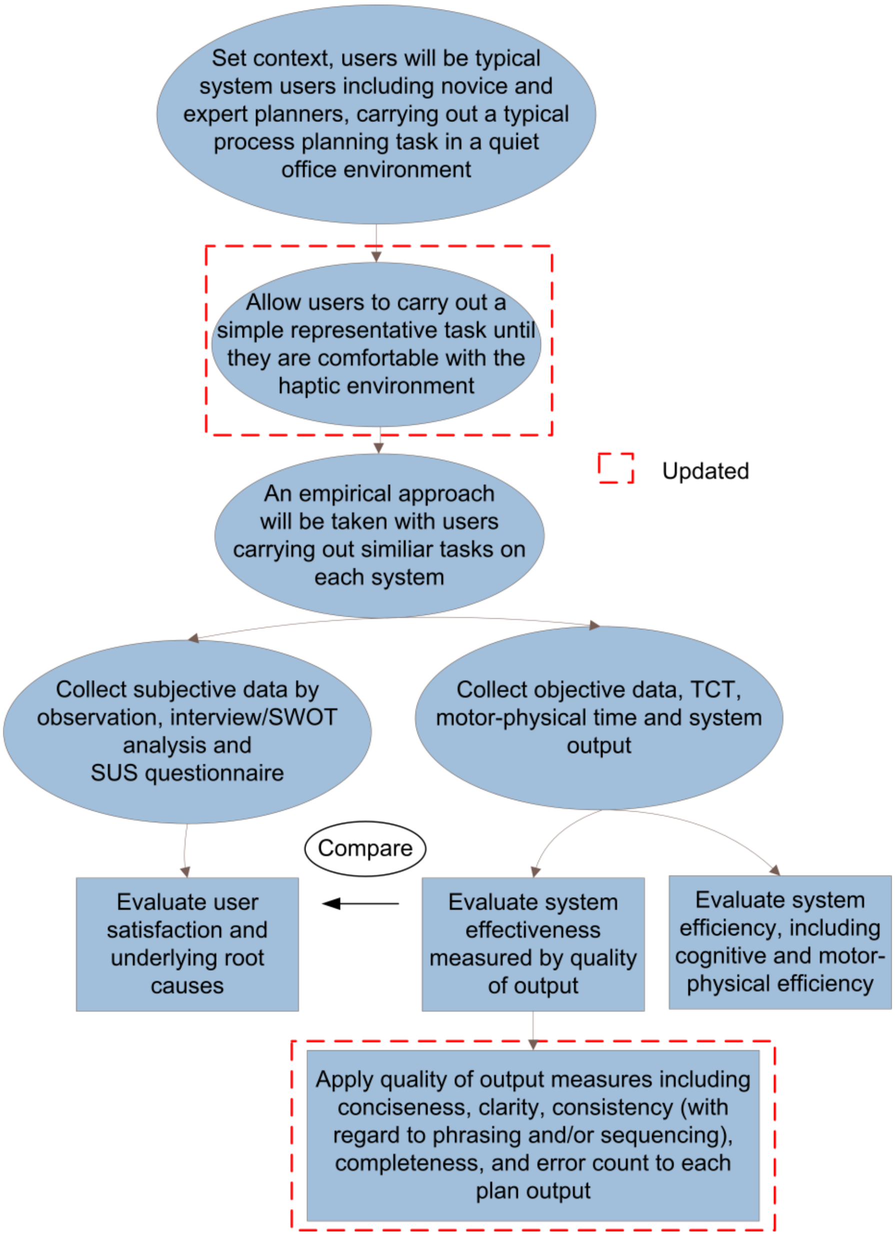


Figure 73 Updated 'Usability' evaluation method for Process planning systems (UEMPPS)

7.5 Experimental Method

The improved experimental method was followed as indicated above. Implementation differences include a change in context with only expert users, more complex tasks and only one process planning system being evaluated. Task 1 was similar to the previous task in the pilot study. This allowed a comparison between the two versions of HAPP with regard to system efficiency. The following tasks, Tasks 2, 3 and 4, were used to validate the extended functionality.

7.5.1 Tasks

Four tasks were defined at differing levels of complexity to compare and assess the third version of HAPP.

7.5.1.1 Task 1

Task 1 comprised a drill jig component which was a straightforward part that requires one set up and four cutting operations; this is similar to the parts used in Chapter 6 and allowed a comparison of system efficiency between the two versions of HAPP. This also serves as a warm up task with each participant simulating the machining of the part four times.

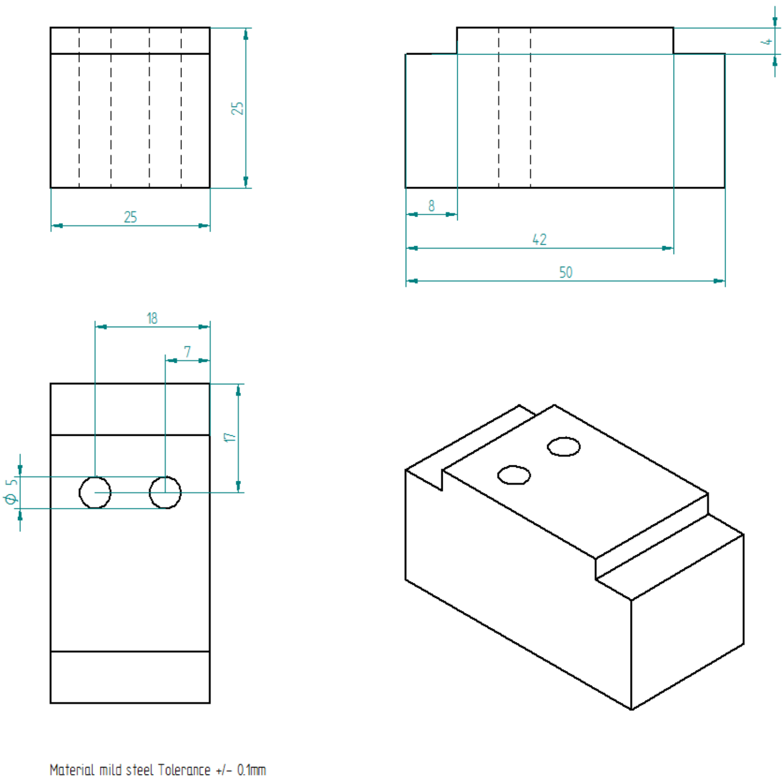
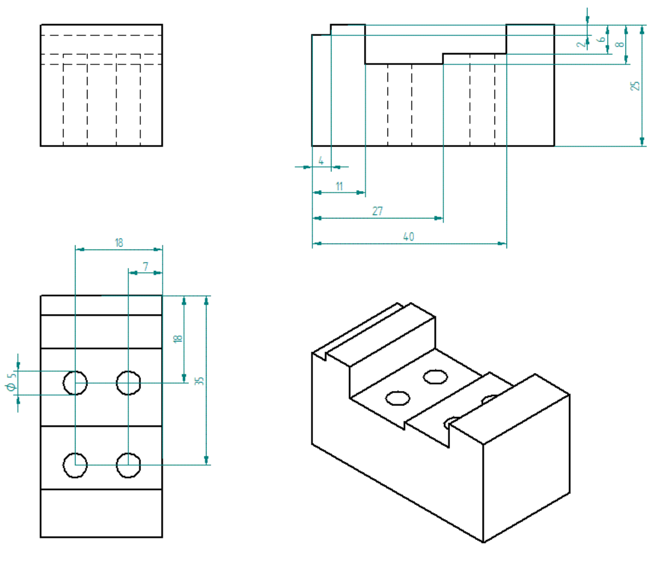


Figure 74 Drill Jig

7.5.1.2 Task 2

Task 2 involved the haptic machining of a Support Base (Part Number: HWEPS1352) which requires two operations, seven cutting sequences, two cutting tools and one work holding device. All operations could be carried out within one set up.

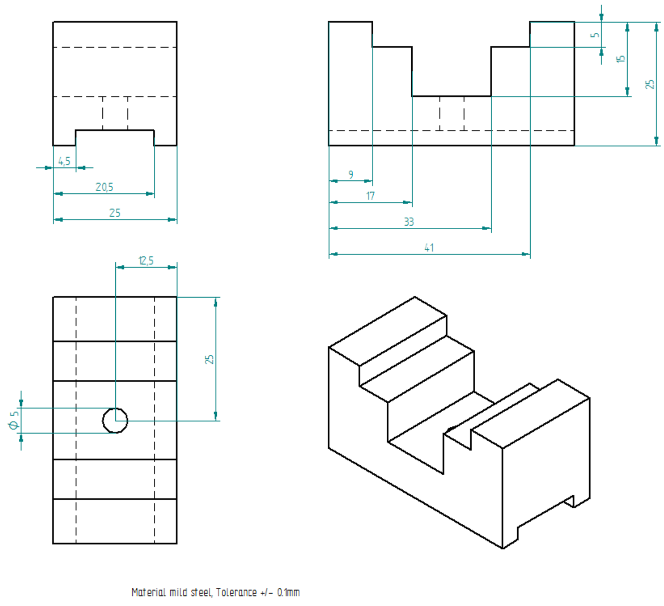


Route sheet			
Operation Number	Machine Description	Operation Description	Tooling details
10	Vertical mill	Locate billet in machine vice	Machine vice
		Mill slot Width 16mm Depth 8mm	16mm diameter slot mill, 4 flute
		Mill shoulder Width 4mm Depth 2mm	16mm diameter slot mill, 4 flute
		Mill shoulder Width 13mm Depth 6mm	16mm diameter slot mill, 4 flute
		Drill through holes Hole diameter 5mm	5mm diameter drill
20	Fitting bench	Deburr and examine	File
Operation Sheet			
Operation Number	Cutting Speed	Cutting Feed	Machining Time
10a	497 RPM	497 mm/minute	0.1 minutes
10b	497 RPM	497 mm/minute	0.1 minutes
10c	497 RPM	497 mm/minute	0.1 minutes
10d	1909 RPM	0.20 mm per/rev	0.07 minutes
10e	1909 RPM	0.20 mm per/rev	0.07 minutes
10f	1909 RPM	0.20 mm per/rev	0.07 minutes
10g	1909 RPM	0.20 mm per/rev	0.07 minutes
Tool List			
	Slot mill 16mm, 4 flute		
	5mm diameter drill		
	Machine vice		
	File		

Figure 75 Example 1: Part number HWEPS1352 - Support Base and benchmark plan

7.5.1.3 Task 3

Task 3 involved the planning of a more complicated variant of the first part. The Alignment Block (Part Number HWEPS06) requires five cutting sequences over three operations. Two cutting tools are required and one change of set up. The two separate milling operations are carried out in the X and Y axes and the entire job can be set up using one work holding device.

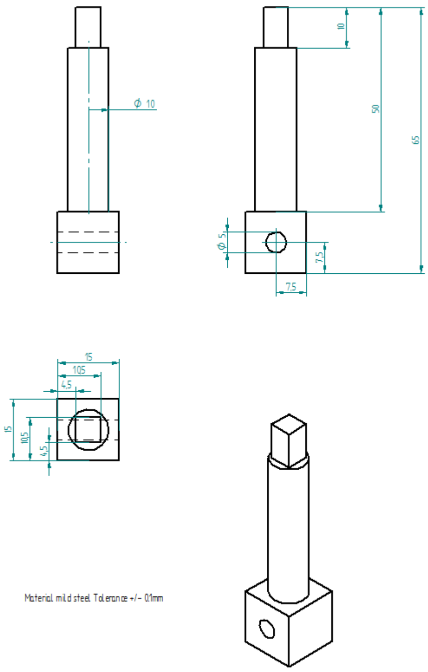


Route sheet			
Operation Number	Machine Description	Operation Description	Tooling details
10	Vertical mill	Locate billet in machine vice	Machine vice
		Mill slot Width 16mm Depth 15mm	16mm diameter slot mill, 4 flute
		Mill shoulders Width 8mm Depth 5mm	16mm diameter slot mill, 4 flute
20	Vertical mill	Locate billet in machine vice	Machine vice
		Mill slot Width 16mm Depth 3mm	16mm diameter slot mill, 4 flute
	Vertical mill	Drill through hole Hole diameter 5mm	5mm twist drill
30	Fitting bench	Deburr and examine	File
Operation sheet			
Operation Number	Cutting Speed	Cutting Feed	Machining Time
10a	497 RPM	497 mm/minute	0.2 minutes
10b	497 RPM	497 mm/minute	0.1 minutes
10c	497 RPM	497 mm/minute	0.1 minutes
20a	497 RPM	497 mm/minute	0.15 minutes
20b	1909 RPM	0.20mm per/rev	0.04 minutes
Tool List			
	Slot mill 16mm, 4 flute		
	5mm diameter drill		
	Machine vice		
	File		

Figure 76 Example 2: Part number HWEPS006 – Alignment Block and benchmark plan.

7.5.1.4 Task 4:

The fourth task requires the machining of a Chuck Key. To manufacture this component two processes are required: turning and milling. The five operations include seven cutting sequences and three cutting tools. Two different types of work holding device are necessary.



Route sheet			
Operation Number	Machine Description	Operation Description	Tooling details
10	Centre Lathe	Grip material in chuck 60 mm projection	4 Jaw chuck
		Face bar Remove 1mm	Right hand knife edge tool
		Turn outside diameter Diameter 10 mm Length 50mm	Right hand knife edge tool
20	Fitting bench	Deburr and examine	File
30	Vertical mill	Locate billet in machine vice	Machine vice
		Mill shoulders Depth 10mm	16mm diameter slot mill, 4 flute
40	Vertical mill	Locate billet in machine vice	Machine vice
		Drill through hole Hole diameter 5mm	5mm twist drill
50	Fitting bench	Deburr and examine	File
Operation sheet			
Operation Number	Cutting Speed	Cutting Feed	Machining Time
10 a	398 RPM	0.25mm per/rev	0.5 minutes
10 b	398 RPM	0.25mm per/rev	0.03 minutes
30a	497 RPM	497mm/minute	0.14 minutes
30b	497 RPM	497mm/minute	0.14 minutes
30c	497 RPM	497mm/minute	0.14 minutes
30d	497 RPM	497mm/minute	0.14 minutes
40	1909 RPM	0.20mm per/rev	0.05 minutes
Tool List			
	Right hand knife edge tool		
	End mill 16mm, 4 flute		
	5mm diameter drill		
	Machine vice		
	File		

Figure 77 Example 3: Part number HWEPS0010 – Chuck Key and benchmark plan

7.6 Results and associated analysis

The structure of the results and their analysis is set out as outlined in Chapter 6, i.e. separated into objective and subjective data. The objective data shows the effectiveness and efficiency of the system. The subjective data captures the satisfaction of the users and their perception of the system's learnability. Finally a discussion of the effectiveness of the evaluation method is presented.

7.7 Objective results

Tasks 2,3 and 4 are initially discussed and the effectiveness of the plans generated shown. This is followed later by an analysis of the efficiency found by Task 1.

7.7.1 Effectiveness

In this phase of the experiment the results were shown on a radial plot. The results are normalised to allow the measures to be demonstrated on the same axes. This approach highlights any variance between the automatically generated process plan and the benchmark plan with regard to the defined measures, thus highlighting the effectiveness of HAPP. The measures of effectiveness are identical to the previous experiment except in this case the measures were applied to each element of the process plan. Consistency was further refined and instead of looking at consistency of information for a specific machining operation, it was applied more comprehensively by evaluating instruction phrasing and instruction sequencing. Consistency with regard to phrasing was measured by awarding a point for the consistent use of a particular phrase for a specific machining instruction. This was recorded by giving each possible machining sequence an identification number. For example: "Locate billet in machine vice drill through holes, mill shoulder mill slot, mill slot, deburr and examine" is named Sequence 1. Another sequence might be "locate billet in machine vice, mill shoulder, mill slot, mill slot, drill through holes, deburr and examine" and is named Sequence 2. The identification number for each plan was then shown in the radial plot. Thus if the same machining sequence, e.g. Sequence 1, was used by all planners then this would be shown in the plot as having no variation. Further as more different machining strategies are applied these strategies may incur different costs. Therefore to highlight these differences a bar chart is included demonstrating where operators chose strategies that may result in different manufacturing cost.

7.7.1.1 Task 2

An example of a process plan generated by HAPP for the support base HWEPS1352 (Figure 75) is illustrated in Figure 78. The measures of the plans' effectiveness and their variation between users are illustrated in Figure 79.

Route sheet					
Operation Number	Machine Description	Operation Description	Tooling Details		
10	Vertical mill	Locate billet in machine vice	Machine vice		
		mill slot, width 32mm, depth 6mm	Slot mill 16mm, 4 flute		
		mill slot, width 16mm, depth 6mm	Slot mill 16mm, 4 flute		
		mill shoulder, width 4mm, depth 2mm	Slot mill 16mm, 4 flute		
		drill through holes, 5mm diameter	5mm diameter drill		
20	Fitting bench	Deburr and examine	File		
Operation sheet					
Operation Number	Cutting Speed (RPM)	Cutting Feed	Machining Time (minutes)		
10, a	497	497mm/minute	0.2		
10, b	497	497mm/minute	0.1		
10, c	497	497mm/minute	0.1		
10, d	1909	0.2mm per rev	0.05		
10, e	1909	0.2mm per rev	0.05		
10, f	1909	0.2mm per rev	0.05		
10, g	1909	0.2mm per rev	0.05		
Tool List					
Machine vice					
Slot mill 16mm, 4 flute					
5mm diameter drill					
file					
Cost sheet					
Operation Number	Description	Setting up (seconds)	Machining (seconds)	Tearing down (seconds)	Examination (seconds)
10	clamping billet	30			
10	Slot mill 16mm, 4 flute	300			
10	Slot mill 16mm, 4 flute		12		
10	Slot mill 16mm, 4 flute		6		
10	Slot mill 16mm, 4 flute		6		
10	Slot mill 16mm, 4 flute			30	
10	5mm diameter drill	300			
10	5mm diameter drill		3		
10	5mm diameter drill		3		
10	5mm diameter drill		3		
10	5mm diameter drill		3		
10	5mm diameter drill			30	
20	Deburr and examine				120
Total Time	seconds	846			
Total Cost	£	11.844			

Figure 78 Example of HAPP generated process plan for Support Base (HWEPS1352).

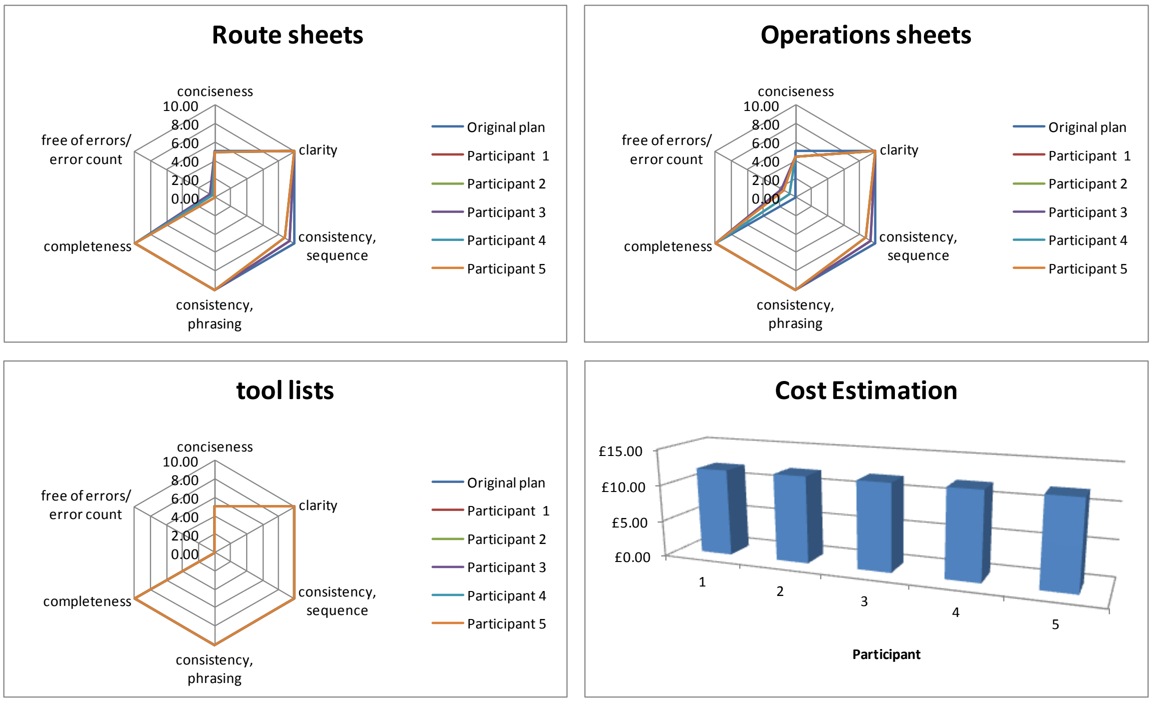


Figure 79 Comparison of generated process plans and original process plan of support base for effectiveness

It should be noted that in Figure 79 where there is no variation between participants data, only the final participants data is clearly rendered with the others being hidden beneath. However the generated plans can be seen to be concise, clear and complete with consistent phrasing. Different machining strategies were captured for later analysis. Estimated costs can be seen to be identical. The slight difference in variation in the conciseness of the operations sheet is due to the repetition of a unit of measure in the benchmark plan where it is only stated once in the header of the generated plan. The variation in the error account is due to the accuracy of some cut dimensions being out of tolerance by approximately 1mm. The variation in the consistency of sequence is due to operators following one of three machining strategies:

1. Machine a deep slot, followed by large shoulder, small shoulder and through-holes.
2. Machine a wide slot, followed by a deep slot, small shoulder and through-holes.
3. Machine large shoulder, deep slot, small shoulder and through-holes.

7.7.1.2 Task 3

An example of a process plan generated by HAPP for the Alignment Block HWEPS006 (Figure 76) is illustrated in Figure 80. The measures of the plans' effectiveness and their variation between users are illustrated in Figure 81.

Route sheet					
Operation Number	Machine Description	Operation Description	Tooling Details		
10	Vertical mill	Locate billet in machine vice	Machine vice		
		mill slot, width 32mm, depth 5mm	Slot mill 16mm, 4 flute		
		mill slot, width 16mm, depth 15mm	Slot mill 16mm, 4 flute		
20	Fitting bench	Deburr and examine	File		
30	Vertical mill	Locate billet in machine vice	Machine vice		
		mill slot, width 16mm, depth 3mm	Slot mill 16mm, 4 flute		
		drill through hole diameter 5mm	5mm diameter drill		
40	Fitting bench	Deburr and examine	File		
Operation sheet					
Operation Number	Cutting Speed (RPM)	Cutting Feed	Machining Time (minutes)		
10, a	497	497mm/minute	0.2		
10, b	497	497mm/minute	0.2		
30, a	497	497mm/minute	0.15		
30, b	1909	0.2mm per rev	0.05		
Tool List					
Machine vice					
Slot mill 16mm, 4 flute					
file					
5mm diameter drill					
Cost sheet					
Operation Number	Description	Setting up (seconds)	Machining (seconds)	Tearing down (seconds)	Examination (seconds)
10	clamping billet	30			
10	Slot mill 16mm, 4 flute	300			
10	Slot mill 16mm, 4 flute		12		
10	Slot mill 16mm, 4 flute		12		
10	Slot mill 16mm, 4 flute			30	
20	Deburr and examine				120
30	clamping billet	30			
30	Slot mill 16mm, 4 flute	300			
30	Slot mill 16mm, 4 flute		9		
30	Slot mill 16mm, 4 flute			30	
30	5mm diameter drill	300			
30	5mm diameter drill		3		
30	5mm diameter drill			30	
40	Deburr and examine				120
Total Time	seconds	1326			
Total Cost	£	18.4314			

Figure 80 Example of HAPP generated process plan for Alignment Block (HWEPS006)

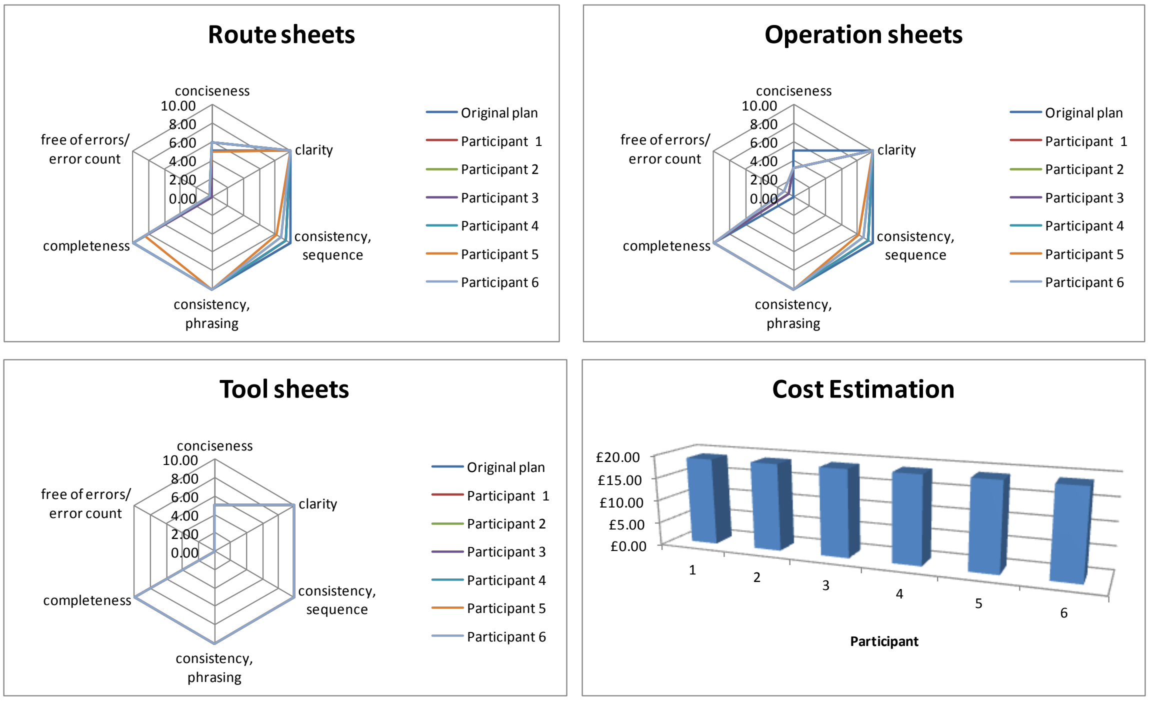


Figure 81 Comparison of generated process plans and original plan of alignment block for effectiveness

It should be noted that as in previous figures, in Figure 81 where there is no variation between participants data, only the final participants data is clearly rendered with the others being hidden beneath. For Task 3 the plans can also be seen to be consistent, complete, clear and concise. The variation in the sequence illustrates the capture of different strategies used in later analysis. The generated operation sheet is slightly more concise than that of the benchmark plan due to the same strategy being taken by all participants in choosing to machine one large slot instead of two shoulders on either side of the deeper slot. The lack of completeness seen in the route sheet for participant 5 was due to a bug in the plan parser which was subsequently corrected.

7.7.1.3 Task 4

An example of a process plan generated by HAPP for the Chuck Key (Figure 77) is shown in Figure 82. The measures of the plans' effectiveness and their variation between users are illustrated in Figure 83.

Route sheet					
Operation Number	Machine Description	Operation Description	Tooling Details		
10	Centre Lathe	Grip material in chuck, 60mm projection	4 jaw chuck		
		Face bar, remove 1mm	Right hand knife edge tool		
		Turn outside diameter, diameter 10mm, length 50mm	Right hand knife edge tool		
20	Fitting bench	Deburr and examine	File		
30	Vertical mill	Locate billet in machine vice	Machine vice		
		drill through hole 5mm diameter	5mm diameter drill		
40	Fitting bench	Deburr and examine	File		
50	Vertical mill	Locate billet in machine vice	Machine vice		
		mill shoulder, width 3mm, depth 10mm	Slot mill 16mm, 4 flute		
		mill shoulder, width 3mm, depth 10mm	Slot mill 16mm, 4 flute		
		mill shoulder, width 3mm, depth 10mm	Slot mill 16mm, 4 flute		
		mill shoulder, width 3mm, depth 10mm	Slot mill 16mm, 4 flute		
60	Fitting bench	Deburr and examine	File		
Operation sheet					
Operation Number	Cutting Speed (RPM)	Cutting Feed	Machining Time (minutes)		
10, a	398	0.25mm per rev	0.02		
10, b	398	0.25mm per rev	0.52		
30, a	1909	0.2mm per rev	0.05		
50, a	497	497mm/minute	0.13		
50, b	497	497mm/minute	0.14		
50, c	497	497mm/minute	0.14		
50, d	497	497mm/minute	0.13		
Tool List					
Right hand knife edge tool					
Machine vice					
5mm diameter drill					
file					
Slot mill 16mm, 4 flute					
Cost sheet					
Operation Number	Description	Setting up (seconds)	Machining (seconds)	Tearing down (seconds)	Examination (seconds)
10	clamping billet	30			
10	Right hand knife edge tool	300			
10	Right hand knife edge tool		1		
10	Right hand knife edge tool		31		
10	Right hand knife edge tool			30	
20	Deburr and examine				120
30	clamping billet	30			
30	5mm diameter drill	300			
30	5mm diameter drill		3		
30	5mm diameter drill			30	
40	Deburr and examine				120
50	clamping billet	30			
50	Slot mill 16mm, 4 flute	300			
50	Slot mill 16mm, 4 flute		8		
50	Slot mill 16mm, 4 flute		8		
50	Slot mill 16mm, 4 flute		8		
50	Slot mill 16mm, 4 flute		8		
30	Slot mill 16mm, 4 flute			30	
60	Deburr and examine				120
Total Time	seconds	1507			
Cost		£ 20.80			

Figure 82 Example of HAPP generated process plan for Chuck Key (HWEPS0010).

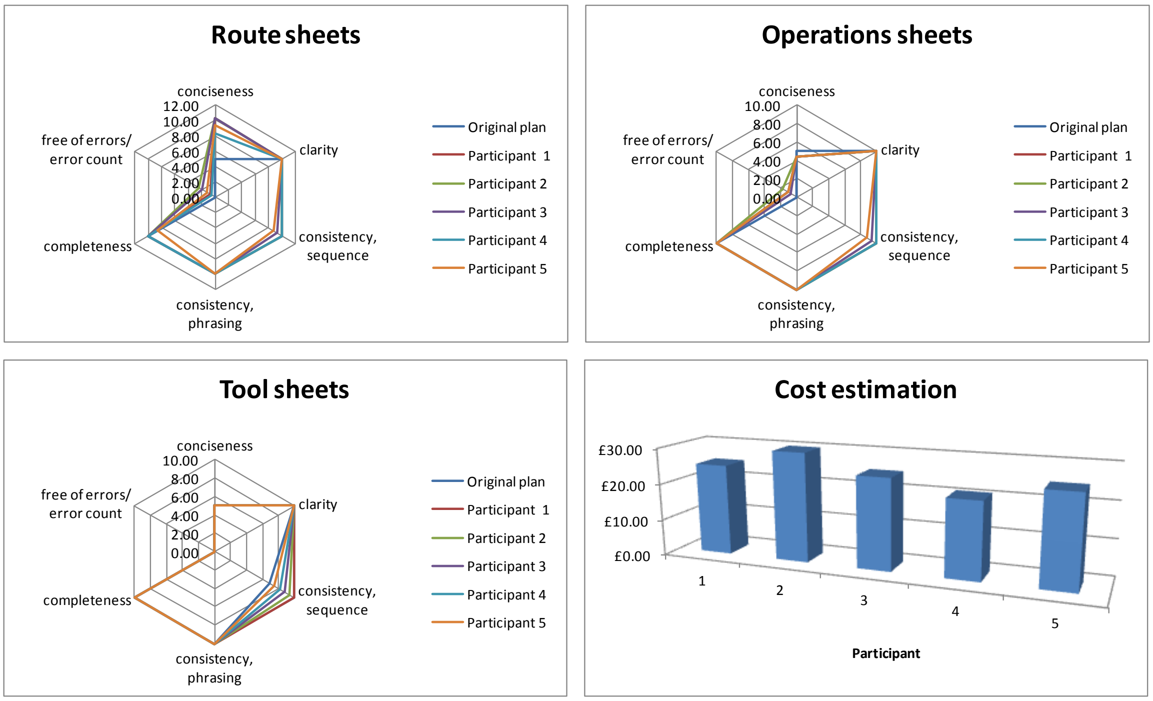


Figure 83 Comparison of generated process plans and original process plan of chuck key for effectiveness

As with the previous figures it should again be noted that in Figure 83 where there is no variation between participants data, only the final participants data is clearly rendered with the others being hidden beneath. The plans generated by each participant for component HWEPS0010 are seen to have comparable clarity, completeness and consistent phrasing to the original plan. The inconsistency in the tool sheet is only related to the order in which the tools are listed and is not considered important since this has no impact on the machining of the part; tool order is indicated in the route sheet. The variation in conciseness of the route sheet and the benchmark plan is due to several factors. Primarily the strategy; some planners opted to machine the shoulders around the square end of the chuck key by placing the turned bar horizontally in a machine vice and then rotating and re-setting the part machined billet for each shoulder, whereas the most experienced planner placed the part machined billet vertically into the machine vice once and used a climb milling approach, thus removing the need for several set up operations. However, it can be seen in general, that all HAPP generated route sheets are less concise than the benchmark plan which can be attributed to the limited ability of the plan parser to group single instructions, e.g. ‘mill shoulders' would replace the four single instructions 'mill shoulder'. The cost estimations are different and can be attributed to the different machining sequences or strategies. This demonstrates the usefulness of HAPP as a tool, not only to compare different machining strategies at the process planning stage, but also as a tool for design-for-machining analysis during the design process.

7.7.1.4 *Discussion of results with regard to system effectiveness*

System improvements were made to improve plan effectiveness with regard to conciseness and completeness, since the instructions in the previous version of HAPP were overly concise and incomplete and a description of machinable features could not be captured. It can be seen that there is no variance in these scores in Figure 79 and Figure 81, with all operators all achieving the same score for completeness and conciseness as in the ideal plan. This demonstrates the feature capture aspect of the system is working correctly. The measure of consistency was modified to include phrasing and sequencing as it is no longer necessary to demonstrate the system's ability to generate consistency with regard to machining parameters. Although when applying this methodology to new systems all three measures of consistency should be applied. From the results of the comparison of the benchmark plan and the plans generated by HAPP it can be seen that HAPP generates plans with standardised phrases, sentences and structure, nullifying inconsistencies in the planning documentation. Planning strategies (sequences) do vary but variants can be analysed and optimised using the time and cost estimation tools demonstrated in the cost sheet of each generated process plan (Figure 78 Figure 80 and Figure 82) However, it is worth noting that with this approach the error count has changed. While there are no large errors, as in the case in the first experiment caused by the operator misinterpreting the drawing, there are some minor errors in cut precision. These are highlighted by the variance of errors in the route and operation sheets associated with Figure 79, Figure 81 and Figure 83. These errors are caused by inaccurate tool positioning due to the softness of the interaction between tool and billet. This softness is caused mainly by slow collision detection in the render loop but the sponginess of the haptic device is also a contributory factor. However these errors could be removed if the operators paid attention to the displayed tool position as well as the haptic guides during tool set up.

7.7.2 *Efficiency*

Initially an analysis of the efficiency of HAPP version 3 is carried out through Task 1, allowing a direct comparison and highlighting improvements in efficiency from version 2. This is then followed by measures of efficiency for Tasks 2, 3 and 4; these not only provide a benchmark measure for later comparison of any process planning system but also provide an insight as to how efficient HAPP is with regard to motor and cognitive processes whilst an operator is planning more complex tasks.

The efficiency of each task is measured using the same approach as applied in the pilot study. The TCT is measured by logging the start and stop time of the task and the times for cognitive

(CC) and motor-physical efficiency (MC) derived. The Task 1 enables a comparison with the previous version of the HAPP software.

7.7.2.1 Task 1

The TCTs for HAPP version 2, HAPP version 3 and the Traditional Process Planning environment captured from the expert user group are illustrated in Figure 84.

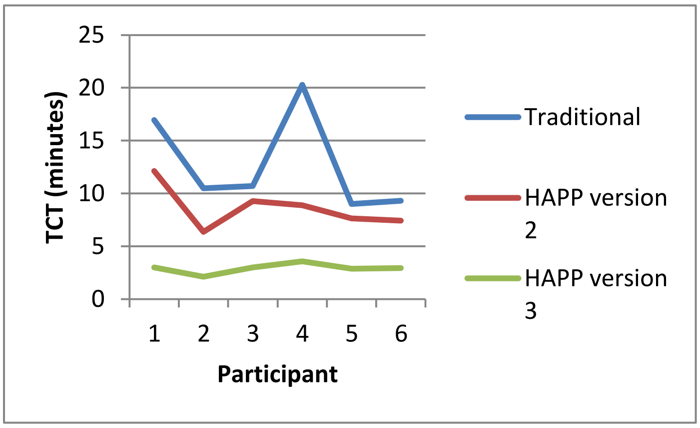


Figure 84 Comparison of process planning environments with regard to efficiency for a simple object with a single set up

The physical motor components of the three systems are illustrated in Figure 85, this again relates to the expert user group.

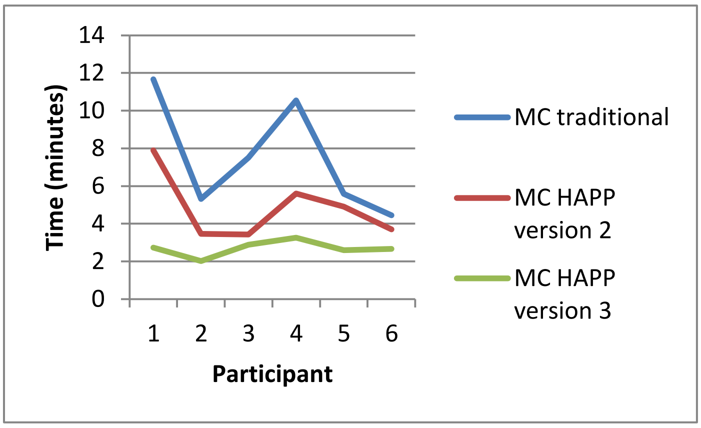


Figure 85 Comparison of MC component of each process planning system for a simple object with a single set up

The cognitive component for each system is illustrated in Figure 86. The CC for the first attempt is included as it could be argued that the CC for the fourth attempt is reduced since the same object has been machined four times. However even the value for the first attempt clearly demonstrates that it is still much lower for HAPP version 3.

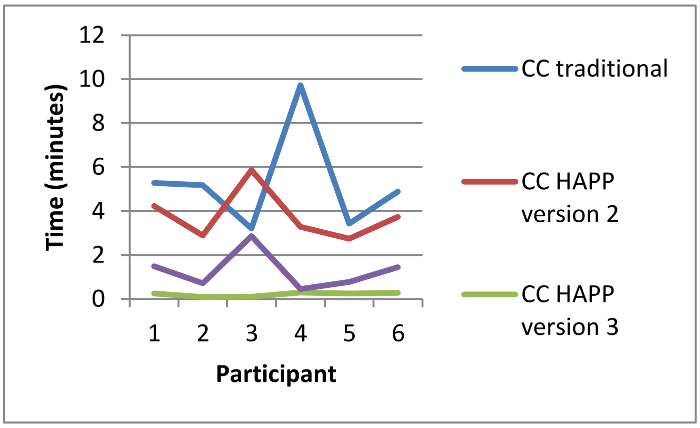


Figure 86 Comparison of CC component of each system for a simple object with a single set up

During the warm up exercises in Task 1 a learning curve with regard to the MC for version 3 can clearly be seen (Figure 87). This provides a quantitative measure which demonstrates improved learnability between versions 2 and 3 since the learning curve can be seen to be steeper for version 2 (Figure 88).

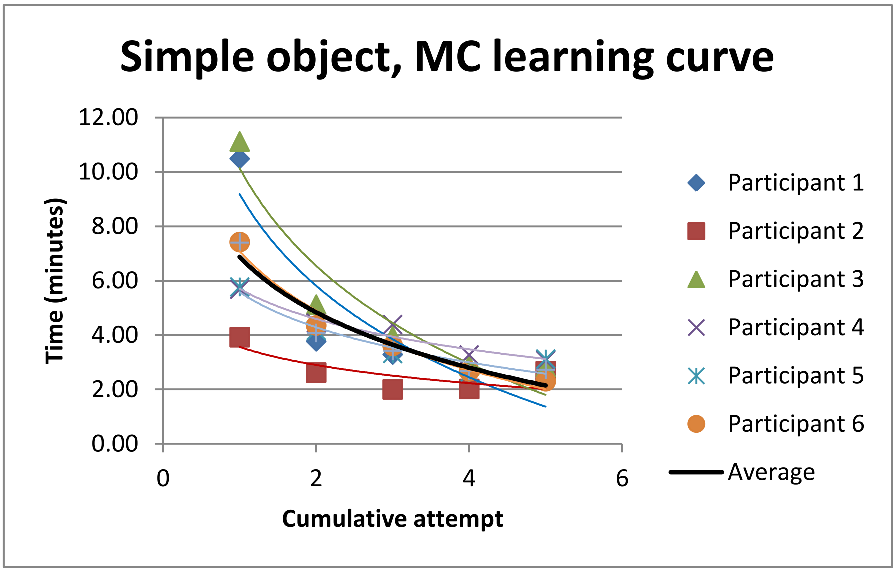


Figure 87 HAPP version 3 learning curve for physical motor component

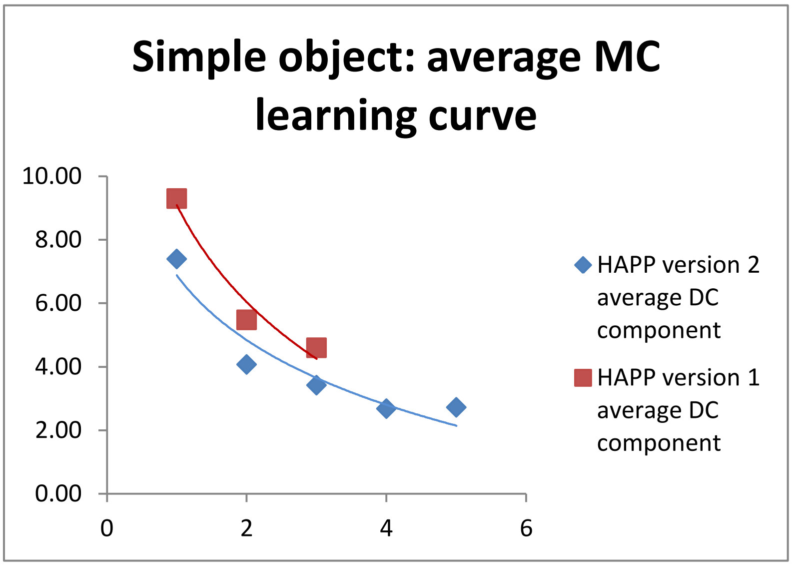


Figure 88 Comparison of average MC learning curve for HAPP version 2 and HAPP version 3

7.7.2.2 Task 2

Figure 89 shows the times taken to simulate the process planning and generate a process plan for the support base (Figure 75). It can be seen that the ratio of time spent planning the CC is extremely low.

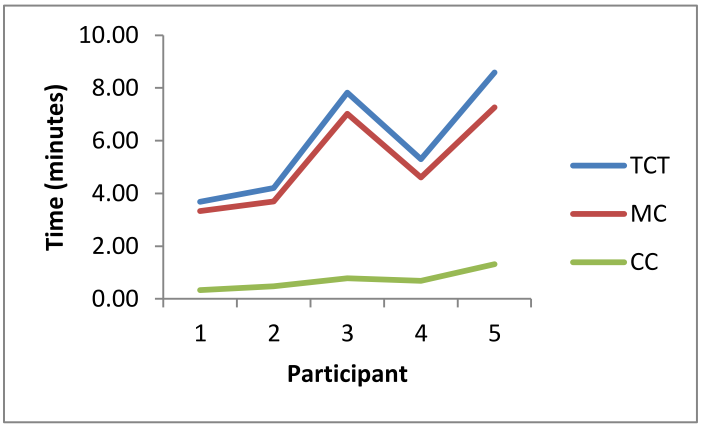


Figure 89 Measure of system efficiency for simulation and knowledge capture with regard to the support base (complex object single set up)

7.7.2.3 Task 3

Figure 90 shows the TCT, MC and CC for the alignment block (Figure 76). It can be seen that even as the planning problem becomes more complex, the CC component is still extremely low.

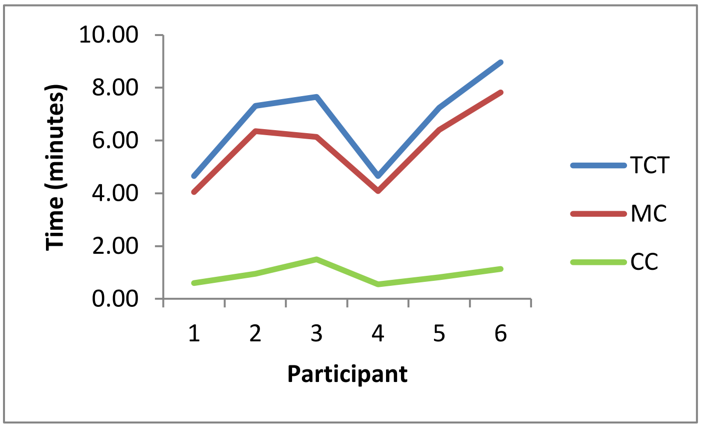


Figure 90 Measure of system efficiency for simulation and knowledge capture with regard to the alignment block (complex object, multiple set up)

7.7.2.4 Task 4

Figure 91 illustrates the TCT, MC and CC for the chuck key Figure 77. Only 3 participants are shown since some logged information was corrupted. However this still demonstrates that with further added complexity, the CC still remains a very small component of the overall time spent carrying out the task.

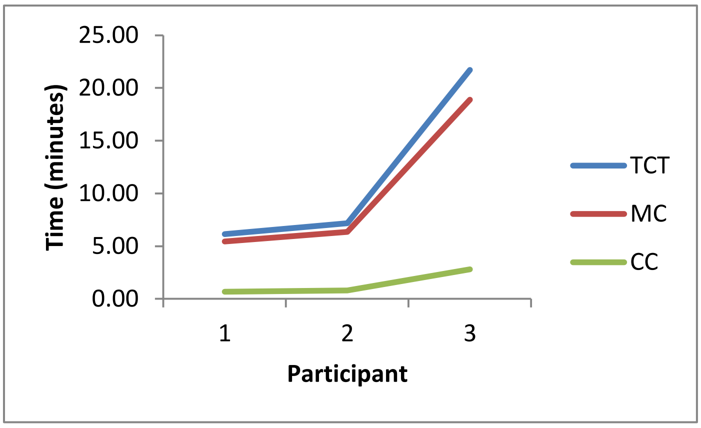


Figure 91 The measure of system efficiency for simulation and knowledge capture with regard to the chuck key (complex object, multi-setup, multi-operation)

7.7.2.5 Discussion of results with regard to system efficiency

From Task 1 it can be seen that the overall system is more efficient than the previous version, the new version demonstrating an efficiency improvement of 66%. When looking at the cognitive and physical motor components, the physical motor component is reduced in comparison to version 2; due to the improvement of the virtual fixtures. It was observed during the experiment that the operator was able to position the tool far more quickly by locating the tool on the feature of the final model haptically rendered within the translucent billet than with the virtual axis locking only. It can also be seen from the results of Task 1 that the cognitive time was further reduced in HAPP version 3. This is also due to the inclusion of the final model suspended in the translucent block; it was noted whilst observing the planners that the 2D drawing was never referred to when planning the part unlike in the first experiment.

The results for Task 2, 3 and 4 all show low cognitive components in spite of the more complex machining tasks. This clearly demonstrates how the haptic virtual environment aids the planner to quickly understand more complex machining problems and realise the necessary sequences to solve them. This supports the literature previously reviewed in surgical planning stating the application of VR in improves the understanding of complex problems (3.3.1).

Finally, although not in response to any of the research questions, functionality was included which enabled planners to review the generated process plans and select the most optimal for manufacture. Interestingly the selected plan for Figure 77 was created by the most experienced planner and was not only considered the most efficient and accurate way in which to machine the part by peer review but also reflected in the lowest estimated manufacturing time and cost generated by the system.

7.8 Analysis of subjective results

The individual SUS scores for the HAPP system are illustrated in Figure 92.

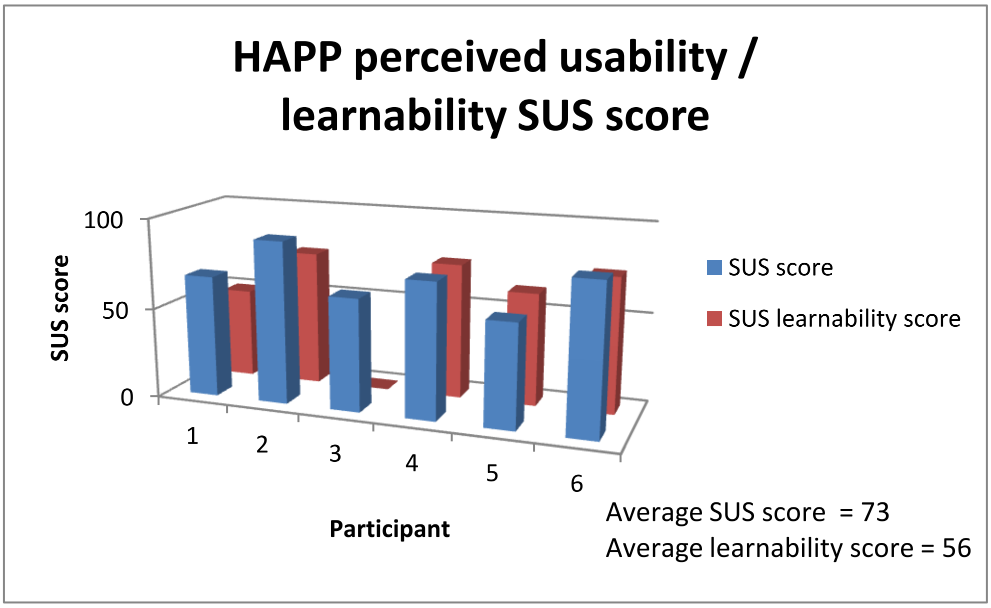


Figure 92 Usability questionnaire results for HAPP by participant.

The average perceived usability score as measured by the SUS questionnaire is 73 with a Standard Deviation (SD) of 12 and Standard Error (SE) of 5. The average learnability score is 56. The average perceived usability and learnability scores for the different process planning systems is illustrated in Table 18.

Table 18 Average perceived usability and learnability scores

	Usability	**Learnability**
HAPP version 3	73	56
HAPP version 2	64	56
Traditional process plans	43	46

The average SUS score of 73 with a Standard Error (SE) of 5 means that the mean usability score falls between 63 and 83, a confidence level of 95%. The adjective-based description of the SUS scores is given in [144] indicating that the mean usability score is considered very good, ranging between high OK to excellent. This is considered to be acceptable considering that all of the participants are experienced machinists but novices with regard to 3D environment interaction. The learnability score is 56. When comparing this to the previous round of experiments the experienced process planners gave HAPP a perceived usability score of 64 and a learnability score of 56. So it can be seen in spite of the added complexity the system modifications have made the system more satisfying to use and at least as easy to learn as the previous version although it should be noted that there is one outlier that reduces the learnability score significantly. Excluding this outlier would reveal a learnability score of over 60.

7.8.1 SWOT analysis

Several observations were made along with participant feedback and the results compiled into a SWOT analysis:

Table 19 SWOT analysis of HAPP (observed or number of times point was commented on).

Strengths	**Weaknesses**
• The HAPP approach was very intuitive and easy to learn, with all users having progressed up the learning curve within a matter of 25 minutes (observed). • Active exploration enabled by the haptic device reduced the need for view changing. For example operators were able to position the drill in the hole to be drilled even when the hole was partially obscured, thus removing the need to change views or the viewing angle, increasing the efficiency of the system (observed). • The virtual fixtures enabled the operators to easily control the cutting path of the manipulated tool (observed). • Good visualization and evaluation (3) • Simple to use (1) • Realistic (1)	• By using the final model as a virtual fixture, operators were able to position the part quickly, although guiding forces or positional coordinate visual rendering is required to enable accurate tool positioning to overcome haptic device sponginess/ object to object penetration or a more effective physics engine (observed) • Operators took some time to relate the range of movement to the haptic device to the rotational range of the manipulated object, instead of rotating the object by 90° at a time some users attempted to move the object 180° resulting in awkward physical positioning of lower arm and wrist whilst holding the haptic device(observed). • Participants found the object snapping to the nearest horizontal or vertical axis a little awkward as occasionally the object would snap to an unintended axis. However, without this and with the haptic device being limited to 3 degrees of feedback it would be very difficult to place an object flat. To improve this a six DoF feedback device could be used(observed). • Does not show if billet is securely clamped(1) • Toggle clamp modelling inefficient to use (2)
Opportunities	**Threats**
• Could be used to capture specialist knowledge as a means of training AI based automated planning systems. (observed) • Could be used specifically for complex jig and fixture planning (1) • Good for training (3) • A future programming aid(1)	• A true 3D visual environment, where operators can accurately perceive object depth is required.(observed)

The SWOT analysis reveals some of the underlying reasons a for the improvements in effectiveness, efficiency and user satisfaction. Strengths include simple to use, good visualisation, active exploration and simple manipulation of cutting tools are all contributory factors to improved user satisfaction and system efficiency. The system has also been described as 'good for evaluation' which can be considered to contribute to system effectiveness, with planners able to experiment with different solutions until the most optimal solution is found. Planning experts have also highlighted further development opportunities which include good for training, a future programming aid and useful for analysing complex jig and fixture planning.

7.9 Analysis of shop floor validation

In order to validate the process planning system outputs, the participants were asked to review the generated process plans and select the optimal plan from all the sequences generated by the users. This was subsequently used to validate the plans via actual machining. The successfully completed components are shown in Figure 93. The key aspect of this validation process was that the operator was not aware of how these instructions had been produced.

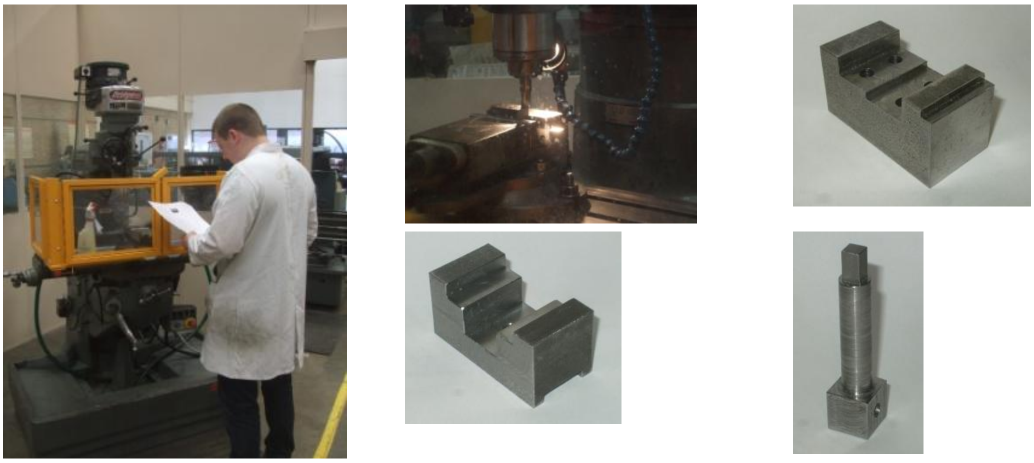


Figure 93 Validation of HAPP system process plans and final products.

During component machining, the technician was provided with a copy of each plan and a drawing and asked to follow the instructions to the letter. To ensure that this was the case he was observed and, when all of the parts were complete, interviewed on the quality of the process plans used. The general feedback from the operator was that he was able to follow the instructions provided, where possible, when accompanied with the part drawing. He also found that they were easily understood, easy to follow, were an accurate representation of machining process requirements and contained enough detail for part completion. The “where possible” comment related to the feeds and speeds generated and embedded into the process plan; these were ignored by the operator and more personally suitable values used for the older machine used for the trials. The HAPP system database can easily be updated with these figures if necessary. The TCTs for the most complex milling example, Task 3, and the turning example, Task 4, were collected and are shown in Table 20. The real world validation TCTs and were found to be well within 12%. The difference in Task 3 can be attributed to a slightly longer set up time required in the real world, the machinist taking an extra cut to machine the slot and insufficient time added between cuts for changing tool depth. The real world time estimate for Task 4 was more accurate however this is not reflected in the real world TCT since one inspection check was missed.

Table 20 HAPP estimated and real world TCT for Task 3 and Task 4

Task	Real world TCT (seconds)	Estimated TCT (seconds)	Accuracy (%)
Task 3	1740	1326	7.6%
Task 4	1320	1507	11%

Overall, the instructions were found to be clear and concise and the machinist did not realise they were computer generated. The response to the questionnaire and successful manufacture of the parts clearly validate the HAPP system and the feasibility of its plans.

7.10 Discussion of evaluation method

It has been shown that the modifications to the test methodology allow a process planning system to be evaluated with regard to ISO 9241-11, assessing system usability, including user satisfaction, system efficiency and system effectiveness. The method guides a user to create a test environment that is clear and consistent and allows the cross comparison between and across process planning systems and different versions of planning systems. The method ensures that the results obtained are comparable and allow the quantification of any differences. Finally the test method recommends a practical application of any system output to confirm the theoretical measure of quality of output.

7.11 Conclusion

In the third iteration of the HAPP application system improvements were made in order to improve the perceived usability, efficiency and effectiveness of the system. These improvements were tested in a realistic environment, focusing on more complex examples and the user group who found the least benefit in the system in the previous software version (the expert user group). It has been demonstrated that the changes have created a system that has been perceived to be more usable and efficient in spite of the more complex tasks, further reducing cognitive load (cognitive component) and motor-physical load (physical motor component) albeit at the slight expense of effectiveness, where the accuracy was affected. Large inaccuracies due to drawing interpretation were removed but smaller inaccuracies were introduced due to the system sponginess. However the overall effectiveness of the system output was improved with the ability to capture and identify machinable features.

7.12 Summary

In the third and final iteration, HAPP included novel contributions where the system was improved to include better haptic guides by including a solid model suspended inside a transparent billet, allowing a tracing approach to be applied during tool positioning and a voxelated tool tip was added to improve the information captured with regard to the feature being machined. Further functionality was also added to allow process planners to simulate more complex machining task, extending the previous version to include turning and multi-face milling. The evaluation method, another novel contribution, was further refined to allow a more complete assessment to the process planning system by applying the measures more thoroughly to the system output, adding a formal measure of learning in the system practice period and adding a practical validation of the system output. Finally the system evaluation with regard to usability was compared to the previous version.

The final version was found to be more satisfying to use, more efficient and generally more effective than the previous version thus further validating research question 3 " How does a haptic process planning environment compare to a commonly used process planning approach with regard to satisfaction of use, efficiency and effectiveness? "

Further since research question 3 has been answered affirmatively, and HAPP provides a more ‘usable’ system than a traditional process planning approach it can be deduced that research question 2 has also been answered positively: " Is this process planning tool perceived to be satisfying to use, efficient and effective, by process planners? "

The final research question: " Can a haptic environment provide a process planning tool that can generate process plans by automatically logging and parsing the user’s interactions? " has also been shown to be true since the effectiveness of the plans has been demonstrated to be of a higher quality than traditional process plans and these plans have also been practically validated by a machinist who had no idea of the plans' origins.

The further refinement and successful application of the evaluation methodology clearly addresses the final outstanding research objective, i.e. research objective 2: " The definition of an experimental set up and usability measures for process planning systems, which allows the usability validation of a process planning system with regard to satisfaction of use, efficiency and effectiveness independent of system platform. "

Chapter 8 Discussion of results

This thesis has argued that a HAPP system would provide a usable environment for process planning. The motivation for proposing this hypothesis came from several sources: literature, an industrial survey and similar work carried in assembly planning. The initial investigation into process planning was inspired through academic literature commenting on the low uptake of process planning by industry. This prompted a closer look at the commercial use of CAPP and process planners from seventeen independent manufacturing companies were interviewed. The survey supported the literature review with only 18% reporting the use of a CAPP system. Responses to the interviews indicated that the low uptake of CAPP systems is in part due to no time saving expected, training is required, systems are too inflexible, difficult to implement and the output is not sufficiently optimised. These issues can be more succinctly described as the systems are not sufficiently 'usable'. During an analysis of CAPP requirements four desirable characteristics of CAPP systems were identified from literature (Figure 2); two of these desirable characteristics which are of key importance when creating a 'usable' CAPP system are ,the system should have a user-friendly interface and involve the user in decision making. These characteristics are not being sufficiently addressed in commercial CAPP systems and this may contribute significantly to their lack of adoption.

Literature surveys of CAPP research revealed that current work is aimed at issues regarding automation, interoperability and operating in dynamic environments. However, during the review an isolated piece of research applying VR to CAPP was discovered. This research highlighted that VR enhanced quick decision making and the facilitation of information sharing through an Intranet, but a closer inspection of the paper revealed VR had only been applied in a very rudimentary way with very basic VR techniques and little actual implementation of process planning functionality. A deeper review of VR revealed VE was being extended to include haptic interfaces (Chapter 3) and that these devices offer an intuitive interface that allows operators to easily pick up, push, pull, rotate and position objects within a virtual environment and carry out tasks in a way with which the operator is already familiar. The ultimate effect of this is that haptic interfaces have been demonstrated to improve task performance in 3D environments where quick and accurate movement is required. They also alleviate visual load by providing an extra channel to communicate information and objects can be moved in a more intuitive manner, so less training is required. A haptic interface fits the human way of working.

An exploration of the literature revealed that researchers have already investigated some areas that can be considered to be components of process planning and that these applications demonstrated that haptic VR provides a means for operators to plan experiment and learn in a safe environment and that an operator's knowledge can be captured and formalized: however, these are fragmented and cannot be considered sufficient to form a process planning system (3.7). The knowledge gaps illustrated in Table 21 led to the first research question and objective.

The first objective of the thesis necessitated the development of a haptic process planning environment that could meet as many of the key requirements necessary to enable a planner to use such a system to generate process plans for some simple objects. This was achieved in Chapter 5 (5.7), a framework was established for a process planning system and an original system developed that was able to meet, in some respect each, of those requirements and produce some initial process plans; thus contributing and addressing a gap in knowledge by creating a novel haptic enabled process planning system. An illustration and description of the functionality is included in the final technical specification in section 7.3.

Table 21 HAPP compared to the literature survey of virtual machining environments and their inclusion of aspects related to process planning.

	Commercial process planning approaches				Haptic virtual machining environments applicable to process planning								HAPP
	Traditional	CATIA	Creo	EdgeCAM	[79] Balasubramaniam et al	[80] Yang and Chen	[81] Zhu and Lee	[82] Zhu and Lee	[78] Chen and Tang	[89] Crison et al	[90][6] Wasfy et al	[83] Chen et al	
Process planning essential requirements													
Drawing interpretation and material evaluation.	x	x	x	x									x
Process selection and sequencing.	x												x
Machine selection and operations sequencing.	x	x	x	x	x	x	x	x	x	x	x	x	x
Tooling selection.	x	x	x	x	x	x	x	x	x	x	x	x	x
Setting the process parameters.	x	x	x	x		x	x			x	x	x	x
Calculate machining times	x	x	x	x									x
Determining the work holding requirements.	x	x	x	x							x		x
Calculate set up time	x												x
Selecting quality assurance methods.	x											x	x
Documenting the process plan.	x	x[7]	x[7]	x[7]									x
Costing the plan.	x												x
Process planning desirable characteristics specific to user													
Involve user in some part of the decision making process	x	x	x	x	x	x	x	x	x	x	x	x	x
Include a user friendly interface					x	x	x	x	x			x	x

Strength with which requirement/characteristic is met Weak	Weak	Strong	Strong

[6] This paper mentions an interface to haptic gloves but no further work regarding this is reported

[7] NC code primarily

However it soon became clear that in building and demonstrating such a system in isolation would provide little contribution to knowledge, what was really needed was a means to quantify the system: particularly as the literature regarding current CAPP systems indicated the lack of usability to be a key issue that HAPP was intended to address. The literature also reveals a paucity of information with regard to the usability of CAPP systems but some work had been carried out with regard to haptic VR systems. From the literature reviewed (Table 22) few researchers have applied a systematic approach aimed at capturing all usability data as defined by the ISO standard and those that do have not clearly defined the context or refined the efficiency measures into cognitive and physical-motor components. This led to the second research question and associated objective.

The second objective of the thesis was met in Chapter 7 (7.12) with the development of UEMPP. The measures of satisfaction, effectiveness and efficiency were derived and grounded in the literature and a cross platform systematic approach for the assessment of usability for process planning systems defined. It is further noted in Table 22 that currently no systematic holistic approach has been previously defined, so this novel piece of work also summarised in the same table , fills a gap in knowledge with regard to usability studies and CAPP.

Even though a systematic approach was defined for the evaluation of a process planning system the contribution to knowledge is limited if any advances cannot be quantified against existing approaches. This led to the third and final research question and supporting research objective.

Table 22 Summary of haptic VR usability studies including a SUS questionnaire.

Application	CAPP	Cross platform	Context defined	Satisfaction measured	Root cause analysis	Learnability	Effectiveness measured	Efficiency measured General	Efficiency measured Motor/ Cognitive
[102] Richter et al	No	No	User not defined	Yes	No	No	Yes	Yes	No
[103] Pirker et al	No	No	No	Yes	No	No	Yes	Yes	No
[104] Rosenburg and Brave	No	No	No	No	No	No	No	Yes	No
[105] Shillito et al	No		Enviroment not defined	Yes	No	No	No	No	No
[106] Scali et al	No	No	User and environment not defined	Yes	No	No	No	Yes	No
[107] Lim et al	No	No	User and environment not defined	Yes	No	No	No	Yes	No
[108] Comai and Mazza	No	No	Environment not defined	Yes	No	No	No	No	No
UEMPP	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**

In Chapter 6 an evaluation methodology is defined and applied to the haptic enabled process planning environment and also to a traditional process planning environment. The tasks selected for both environments and the test methodology ensured a comparison of the two systems could be carried out in a quantifiable way and the analysis and comparison demonstrated that the third and final research objective of the thesis had been met (6.11).

It is in the meeting of these research objectives that the research questions can be answered.

An initial direct comparison of the two systems was found to show that the HAPP system is more satisfying to use, more efficient overall and with lower TCT for the comparable tasks. These are in the main attributed to the significant reduction in the time the user spent thinking about how to manufacture the part, with the time spent on the physical motor aspect of documenting the plan approximately the same between the two systems; although this is expected to be faster and more effective after the operator has used the software approximately ten times according to learning curve theory, producing a measured higher quality of output.

Further development continued advancing the usability of the system whilst also expanding the system functionality to simulate and plan the manufacture of more complex parts. The evaluation method was further refined here to allow for more complex CAPP systems and provide a more complete assessment of CAPP system usability. Once evaluated the third version of the system was found to have made additional gains in terms of satisfaction, efficiency and effectiveness. Although it should be mentioned the gains in efficiency are slightly mitigated by one aspect of the measures of effectiveness with small errors in accuracy appearing where users relied too heavily on the haptic fidelity of the system and disregarded the visual clues.

Overall, this research demonstrates the advantages of a haptic enabled process planning system compared to traditional approaches with regard to system usability and answers research question 3, addressing a gap in current knowledge and contributing to the advancement of process planning systems. In answering question three, research question two is also validated since it was shown that a haptic virtual process planning environment can provide a more usable system for process planning than one of the most commonly used approaches.

The remaining research question, seeks to identify if a process plan can be generated by logging a users interactions from within a virtual environment. It can be deduced that this is true based on the fact the system generated more effective process plans than those created by experts in a traditional way; however, this is also further demonstrated by the application of these plans in a manufacturing environment where the operator had no idea of the plans' origins but was able to successfully able to manufacture the parts.

Also it is shown that the proposed advantages of haptic VR interfaces identified in the literature are also applicable in the area of process planning. The advantage of an intuitive easy to use interface is demonstrated by the short time necessary for participants to learn how to use the system and high scores of perceived satisfaction. The fact that a haptic device allows an object to be quickly and easily manipulated within the VE is reflected in the short time required for operators to generate process plans. The extra communication channel reducing visual load was observed as participants were seen to easily identify when the tool was in cutting mode or not. The advantages that haptic VR environments are able to promote, capture and formalize task specific knowledge are also clearly demonstrated by the effectiveness of the process plans generated. An advantage not foreseen from the literature review was the reduction in cognitive load that would be achieved by the improved visualization and interaction of the haptic VE. This was only determined through the development of the novel usability approach. It is believed that based on this work, in the future haptic virtual environments will empower process planners and allow the planning of more complex jobs at reduced cost and with improved product quality, and novel design for manufacturing as well as intuitive process planning interfaces.

Chapter 9 Conclusion and future work

9.1 Conclusion

This research provides a unique and novel contribution to knowledge by investigating and developing a haptic based process planning system and process planning usability methodology. Where existing process planning approaches have sought to replace process planners, concentrating on AI, this systems aims to empower them. A combination of haptics and VR were used to create a user friendly, intuitive interface that includes the user in the decision making. This has enabled more effective process plans and planning knowledge to be captured more efficiently with a higher degree of user satisfaction than in conventional process planning approaches. It has been demonstrated that:

1. A haptic environment can provide a process planning tool that can generate process plans by automatically logging and parsing the user's interactions.
2. As a process planning tool HAPP is perceived to be satisfying to use, efficient and effective, by process planners.
3. Compared to a commonly used process planning approach HAPP is more satisfying to use, more efficient and more effective.

In addition to this a novel usability methodology has been researched which can be used to compare all forms of process planning system.

Therefore, the aim of this research has been achieved, namely that a novel proof of concept haptic process planning system has been developed which captures and formalizes human expertise. The overall outputs of this work have also proved the original research hypothesis that: " a VR system with a haptic interface can provide a more usable process planning system than the most commonly used current approach."

This approach addresses industry needs as highlighted in the introduction where companies revealed that current CAPP systems were not easily usable, which consequently contributed to their low uptake. This research addresses an area of CAPP system design and usability not currently covered by previous work through the novel application of a new interface to CAPP systems.

9.1.1 Limitations of research and future work

As revealed by literature surveys referenced in Chapter 1, future algorithms are being researched to enable CAPP systems to cope in the dynamic area of manufacturing, derive better decisions from often incomplete pieces of information, have better information sharing through the internet and also be more interoperable.

Although these key areas are being addressed there is one key area, which is not receiving much attention at all that is the area of knowledge capture. Knowledge is considered to be information that has been given context and meaning and has been verified by an expert [152]. It can be explicit or tacit: explicit knowledge is codified whereas tacit knowledge is not. Companies recognise the value in capturing knowledge but find its acquisition and codification time consuming and costly. The addition of knowledge into manufacturing can create added value. Rather than creating CAPP systems that compete in arenas of low value, high volume manufacturing by reducing and automating specialist skills, CAPP has the opportunity to promote and maintain specialist knowledge creating areas of high value manufacturing. This could be of particular interest to countries with high labour costs: but in order to achieve this CAPP systems need to be more usable, they need to fulfil the task of promoting knowledge, capturing knowledge, validating knowledge and then formalizing that knowledge in a format for downstream reuse and should be done in a way that is effective, efficient and satisfying for the operators to use.

How this is achieved is still a major challenge for CAPP, not only capturing local manufacturing strategies but also at the CAPP system inception (assuming it is required to have some level of intelligence in the beginning). This area has seen little investigation to date and VR can be further exploited to achieve this. It has been demonstrated that that haptic VR makes a more usable interface than conventional process planning methods and is capable of capturing tacit knowledge. There is no reason why this approach could not be integrated into generative and variant systems in order to train them in the first place, maintaining and updating that knowledge will be simpler as operators will not be required to learn a new interface but will be working with an abstract model of the machinery they are already familiar with, it may even be possible with sufficient computing power to validate manufacturing sequences from the system without even having to actually manufacture the product. This would allow manufacturing knowledge to be accumulated very quickly.

However in order to achieve this there are still some key areas that need to be addressed within VR, particularly in 3D environments where model complexity is ever increasing.

Depth perception is still a major hurdle and one of the main motivations for this approach was the need for 3D devices to allow the operator to interact with 3D models in a more natural way. However the display is still only a 2D device and the interaction does not fit well. It is difficult to believe planners would prefer to work in 3D glasses all day and even with the stereoscopic vision enabled the depth clues were still not sufficient, with operators wasting time while selecting objects. Research has been carried out with regard to depth perception in VR environments and it has been demonstrated that several clues are needed to enable depth perception. It would be interesting to see if an application with all these depth clues would be sufficient to enable a quick and efficient interaction within a 3D haptic environment suitable for simulating manufacturing tasks, there is also some interesting work being carried out with holograms perhaps these would provide a more elegant solution to the depth perception issue.

A second area is the haptic technology. There are two significant issues here, the first is the device cost and the second the fidelity of rendered forces at interactive rates. In order for haptic enabled process planning to be a solution that can be implemented in industry low cost devices are needed that are not only capable of rendering a wider range of dynamic forces but also devices that can provide 6 DoF. Current haptic devices of this type currently retail at tens of thousands of pounds. Whilst a device with 3 DoF is capable of revealing a lot of information about an object and can simulate 2.5D machining processes it is not sufficient to model the manipulation of objects for clamping and fixturing, neither will it be sufficient for modelling more sophisticated machinery that may be implemented such as a 5 axis CNC machine.

The rendering of dynamic forces is also related to the physical modelling in the simulation. If the acquisition of higher quality information with regard to actual machining processes is required the physical modelling needs to be improved. Current challenges include collision detection, particularly in narrow phase, which with complicated models, model deformation and material removal will cause the failure to meet the required interactive rate. Continued research is required to ensure complex scenes can be modelled accurately and smoothly at interactive rates.

Specific areas and current limitations of within the HAPP system that should be considered for future work are:

1. The extension of the system functionality: in order to be applied in an industrial environment the system should not only be able handle a wider variety

of machine and tool types but also the ability to aid a process planner in a wider array of manufacturing processes such as sheet metal bending, welding, forging etc.

2. Better approaches for material evaluation: for example Finite Element Analysis (FEA) could be included to narrow the gap between material selection for manufacture and material evaluation for design but the challenge here is to carry these out in real time or at least at interactive rates.
3. A better way of checking and validating the knowledge for both manufacturing and fixturing processes this could include better physical modelling which would allow the individual process planner to validate their own plan and/or a means to compare that knowledge to an existing knowledge base. This should also be combined to undo knowledge captured that is rejected.
4. The ability to handle more complex models at interactive rates: an investigation into how can this be achieved is required especially can multithreading be applied to improve simulation speed or would a different model type such as NURBS or volume modelling techniques be more appropriate.

HAPP would provide an ideal interface to train process planning systems or develop some of the rules that current approaches require as eluded to in Section 2.5. To this end an interface into AI systems should be investigated which would allow this system to be loosely coupled to specific CAPP systems but highly cohesive with all.

The need for a platform independent output for CAPP systems has already been discussed and the current system is limited to conventional process plans. Future work should investigate how this knowledge can be formalized in a STEP compliant format creating a more interoperable system.

One of the strengths of software-based approaches is their ability to share information. HAPP is currently limited to a single operator at a PC. Communication and knowledge sharing could be further enhanced by enabling the system to be compatible with internet technology.

With regard to experimental method and evaluation the system which has now been benchmarked against traditional approaches should be extended and compared to other computer based process planning systems with more conventional interfaces.

CAPP for material removal has seen little investigation with regard to the application of VR technologies with the ongoing development of cheaper and faster hardware the potential to integrate and include VR into commercial applications becomes more realisable. Only research carried out at this stage can justify and quantify the potential benefits of this technology and focus development in the correct area.

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